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PREFACE

This issue, Number 1 of Volume 51, contains the papers presented at the Pacific Coast Convention held at Lake Tahoe, California, August 25-28, 1931, and at the South West District Meeting, Kansas City, Missouri, October 22-24, 1931.

In addition to the above papers those for the first three sessions of the Winter Convention, held in New York, N. Y., January 25-29, 1932, are included in this issue. The remainder of the Winter Convention papers will be included in the next issue, Number 2, of the TRANSACTIONS.

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Electrical Equipment for Oil Field Operations

BY HAROLD C. HILL[1]
Non-member

and J. B. Se LEGUE[2]
Associate, A. I. E. E.

INTRODUCTION

IN the application of electricity to the work of drilling for oil and pumping the wells, many problems peculiar to this industry have been encountered. This paper presents some of the more interesting features of these applications and is confined to a discussion of the duty involved and of the design of the apparatus for the purpose.

Electricity for oil field operations was first used in the Eastern fields over 30 years ago, but the extensive use of this form of power did not begin until 10 or 12 years later when it was introduced in the California fields. Most of the new developments which have since been made in the design and use of electrical apparatus for oil well drilling and pumping have first been tried and perfected in the California fields before being adopted elsewhere. This has been due not only to the fact that field conditions encountered there have resulted in many advances in the art, but also to the availability of dependable central station power service in all the fields.

GROWTH OF THE INDUSTRY

Since the first well was completed near Titusville, Pa. in August 1859 the oil industry has had a tremendous growth, oil now being produced in nineteen states from 330,000 wells.

In 1906 there were less than 800 million dollars invested in the oil industry. Today the investment exceeds twelve billions of dollars.

The records of the petroleum industry during the last fifteen or twenty years indicate that it is probably the most highly competitive of American industries, and it is therefore natural that the oil operators are interested not only in costs, but also in the development of the most efficient methods of drilling and producing.

Of the tremendous connected horsepower in the industry in this country, it is understood that only 7 per cent is electrical. In California alone there is one and one-half million horsepower installed, of which only 15 per cent is electrical, which indicates the potential possibilities for electrification.

CABLE TOOL DRILLING

For the past fifteen years there has been an average of 24,000 oil wells drilled per year in the United States by the cable tool and rotary methods, and although the latter is now the predominating one, the cable tool method was the original one employed and is still extensively used. Drilling by cable tools is accomplished by percussion, the bit being suspended from a walking-beam by a manila or steel cable and cutting the formation by the vertical reciprocating motion imparted to it by the rocking motion of the beam. The latter is actuated by a crank and the crank shaft is belt-, gear- or chain-driven. All work of handling the drilling tools, bailing and swabbing the hole and inserting casing is handled by a hoisting mechanism which is a part of the drilling rig.

Nearly all cable tool drillers claim that, as the depth of the well changes, a very close adjustment of the number of strokes of the bit per minute must be made to accord with the natural period of the drilling line and thus obtain the most effective results, and it has therefore been necessary to provide such control in the electrical equipment. This proved to be the chief feature of operation which could not be readily accomplished with strictly standard motor equipment.

Two different methods have been devised to meet this requirement. One of these employs the standard wound-rotor induction motor with two controllers and resistors, the main controller being of standard design for coarse speed adjustment and the auxiliary controller being specially designed with the three secondary phases separate, so that it could be cut in between any two points of the main controller and thus act as a vernier adjustment of speed. The total number of control points thus made available is equal to the product of the number of points in each controller, and is usually from 135 to 160.

The other method makes use of two oil well pumping motors of the two-speed wound-rotor induction type, mechanically installed to operate in multiple to handle the drilling operations, and so arranged that one motor and control may be left permanently at the well to pump it after it is "brought in" as a producer. Each of these motors has its individual control equipment, consisting essentially of a controller, a resistor and a pole-changing switch. The controllers are both operated by ropewheels from the driller's position at the derrick, and these wheels are arranged for separate operation to give individual speed control of each motor, or may be locked together to give simultaneous control of both. When a small change in speed of the twin-motor drive is needed during drilling, one controller is moved one or more points beyond the position of the other, thus shifting part of the load from one motor to the other. This changes the resultant slip of the combination and gives the change in speed desired. On hoisting duty, for which the power demand is much higher, the ropewheels are locked together and

1. Sales Engg., General Electric Co., Los Angeles, Calif.
2. Engg. Dept., General Electric Co., Los Angeles, Calif.

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the motors are controlled as a single unit, dividing the load evenly.

Some oil companies have succeeded in drilling with cable tools by using only a single two-speed motor equipment with less than ten points of control available, and they have claimed the operation was satisfactory, but so few control points would not be acceptable to most drillers and so an auxiliary control unit must be added. Such an equipment may be left at the rig permanently for the purpose of pumping the well after it is drilled provided that the size of motor required for pumping is somewhere near that necessary for drilling. The auxiliary control unit is moved to the next new location.

There is one other speed characteristic which cable tools require to drill most effectively, that being an almost free drop of the tools on the down stroke, followed by a slower pick-up. This is accomplished without special design of apparatus, by operating the motor with secondary resistance in circuit when drilling, thus giving a wide speed regulation with change in load. The best motion is obtained if the motor is fairly heavily loaded, but the drilling load is moderate in comparison with the hoisting load and does not necessarily increase with the depth. Therefore, when the hoisting duty is heavy because of the high speeds at which it is desired to handle heavy loads, and so calls for a motor of large capacity, it has been proposed to use a two-speed motor with ample capacity for drilling on the low-speed connection with secondary resistance in circuit. The full capacity of the high-speed connection would then be available for the heavy work.

A brief analysis of the motor characteristics suitable for cable tool drilling begins with the fact that it is first necessary, as already indicated, to adjust the secondary resistance of the motor or motors to get an average speed in strokes per minute to accord with the natural period of the drilling line. The time for one complete stroke then becomes temporarily fixed, and the best motion of the bit is obtained when the motor responds quickest to the changes in load during that stroke. On the down stroke, the rate of increase in speed is retarded by rotor inertia and limited by the available torque to accelerate. On the up stroke, the rate of decrease in speed is retarded by the rotor inertia and is also affected by the amount of torque available in excess of that required to lift the total weight of drilling tools and suspended line. Thus, in either case, low armature inertia is essential for best results. On the down stroke, high torque is desirable, and on the up stroke, low torque over and above that required to lift the load.

These requirements are well met with a motor having fairly high torque and low $W R^2$, and so geared or belted to the load as to be run on a reduced speed point of the controller when drilling, and under those conditions loaded up as much as possible consistent with its thermal capacity. With a motor assumed to be thermally large enough for the service, a measure of its effectiveness on actual drilling is the maximum torque in lb-ft., divided by ($W R^2 \times$ drilling r. p. m. of motor).

A capacity of 50 hp. is usually sufficient for drilling to a depth of 1,500 ft. and, under some conditions, to 2,000 ft. With a 75-hp. motor, wells have been successfully drilled to as great a depth as 7,300 ft. but more capacity is desirable for deep drilling to enable tools and bailer to be removed from the hole at high speeds. For this reason a rating of 125/45 hp. has been under consideration for the proposed two-speed motor already mentioned.

Rotary Drilling

Rotary drilling is accomplished, as its name implies, by a rotary motion of the drilling bit. The bit is of course designed for boring, and is supported at the end of a column of screwed-joint drill pipe which is suspended by blocks and tackle from the top of the derrick and raised and lowered by a hoist mechanism located at the edge of the derrick floor and known as the draw works. The drill pipe is turned by a rotary table through an opening in which the pipe is suspended. The table is mounted on the derrick floor and is driven from the draw works.

The rotary drilling process requires the circulation of a heavy mixture of mud and water down through the drill pipe, out through holes in the bit and back to the surface, carrying the cuttings with it and "mudding off" the walls of the hole, preventing cave-ins and holding back high pressure gas. Drilling is thus a continuous process except when it is necessary to replace worn bits or recover pipe which has twisted off. The pipe is then hoisted out in lengths which can be stacked in the derrick and is afterward replaced in the hole for the resumption of drilling.

Steam or internal combustion engines or electric motors are used for motive power, the draw works and each of the two mud pumps being driven by separate power units.

Draw Works Drive. A good idea of the range of conditions to be met by the power equipment may be gained from the following approximate figures, which are mentioned as a matter of interest, but a complete discussion of which is prevented by lack of space.

Ordinary drilling loads are from 30 to 100 hp. at speeds of 50 to 120 r. p. m. of the table. The operations of coring and reaming require low speeds, from 15 to 40 r. p. m. and the horsepower required is from 10 to 25 hp.

Under hoisting duty, the same engine or motor must deliver from 100 to 250 hp., with peaks in extreme cases up to about 600 hp., over a range of hook speeds from 90 to 180 ft. per min. The load of hoisting the empty traveling block varies from about 10 to 165 hp. with speeds up to 350 ft. per min.

The steam engine has been popular for many years

because its speed and torque characteristics make it admirably fitted to perform all the necessary operations in rotary drilling. Particular attention has therefore been given toward duplicating or improving upon steam engine characteristics in devising electrical equipment to do the work. This has been done with motors and control departing very little from standard electrical design, but a few interesting features are worthy of mention.

Standard wound-rotor induction motors up to 200 hp. have been used for moderate and even deep drilling, the speed and torque characteristics meeting the requirements quite well when the motor is provided with suitable control equipment. Deep drilling requires relatively large horsepower capacity for the heavy hoisting duty, but the rotary table loads do not increase proportionately with depth. As satisfactory control of an induction motor is difficult to obtain under light loads and slow speeds, special means have been devised to get good results. In some cases, additional resistance has been inserted in the secondary circuit of the motor by means of an auxiliary controller, but two more efficient and generally better methods are now being used.

One method is to use two motors in multiple, driving the draw works through a special twin-drive gear reduction unit. One motor is used for drilling, coring, reaming and other relatively light duty, and the two motors together are used for hoisting. Magnetic control equipment for each motor, suitably interconnected and interlocked, makes the handling of the equipment very simple for the driller. Not only is the speed control at light loads thus materially improved, but the twin motors have the advantage of low total armature inertia, which permits rapid acceleration and reversals. Installations of two 125-hp. and also of two 150-hp. motors have been made.

The other method is the use of a Y-delta wound-rotor motor, six stator leads being brought out to enable the motor to be run on the Y-connection for light work and on the delta connection for heavy work. Motors of this type developed for this service are rated 250/85 hp. and 250/125 hp., and are designed for low armature inertia.

Both of these methods have worked out very well in rotary drilling service and have overcome the difficulty of satisfactorily controlling the standard wound-rotor motor equipment in the large sizes.

Electrically, the control equipment for draw works motors follows the standard practise in industrial motor applications except that provision must be made in the design of the secondary resistor for running the motor at very low speeds under some light load conditions, such as rotating the drill pipe at low speed with the bit raised off bottom, which is a practise generally followed when changing tours, and, in some fields, when the crew is eating lunch. The smaller sizes of motors are governed by manually-operated controllers, and the larger sizes by full magnetic control with a master switch. The controller or master switch is operated by a ropewheel or handwheel located on the draw works post at the driller's position, the main control equipment being set back behind the draw works or even at some distance from the well if gas conditions make it advisable.

Acceleration of the motor by magnetic control is automatically governed by either time-limit or current-limit relays, each having its advantages and the preference of some operators. Both prevent the operator from cutting out the secondary resistance too rapidly for the best rate of acceleration, and they reduce the current peaks and the possibility of damage to the mechanical equipment. The definite time relays are generally set for a total time delay of about 8 seconds, with 2½ seconds allowed at the point giving maximum motor torque, so as to insure that this point is not passed until the load is partially accelerated. When current-limit relays are used, they are adjusted to suit the load conditions encountered and keep the current peaks from exceeding reasonable limits. In general, the use of accelerating relays in conjunction with magnetic control has been one of the chief factors in making a pronounced success of electric drive for deep rotary drilling.

Mud Pumps. Fully as important as any other part of the rotary drilling rig are the mud pumps, and they are subjected to some of the greatest abuses. These pumps are of the positive displacement piston type, and for electric drive include a reduction gear which is usually V-belt driven from the motor. The speed of the crank shaft varies from 20 to 50 r. p. m. and is desired to be reduced occasionally to the point of stalling. The fluid pressure for 7,000-ft. depths will run as high as 700 lb. per sq. in. and it is estimated that with increased depths, pressures in excess of 900 lb. will be required for normal circulation of the mud in the well. Higher pressures are occasionally required in emergencies in some localities, these being obtained by compounding the pumps, the discharge of one being piped to the intake of the other. Each rig is equipped with two or more pumps, all but one being stand-by units.

Only a few years ago the requirements averaged from 60 to 100 hp. per unit, but today the tendency is to use larger pumps requiring up to 250 hp.

The flow of mud is frequently retarded or stopped by plugging of the holes in the bit or restrictions elsewhere along the line of flow, and it is preferable, in order to avoid breakage from high pressure developed by the pump under such conditions, and also to warn the driller of the trouble developing, that the speed be reduced automatically, even to the stalling point, as the pressure increases. Steam pumps have this desirable speed-pressure characteristic, and electric drive may be controlled to do likewise. A standard type of wound-rotor induction motor is employed, but

as normally the pump is run at full speed, the torque of the motor with short-circuited collector rings would, in case of clogging of the mud line, increase sometimes beyond the breaking strength of the pump without a sufficient reduction in speed to avoid such damage. Such a reduction may be made by secondary resistance, and recently one of the electrical manufacturers, in cooperation with a California oil company, made an installation in which a permanent block of resistance and reactance was put in the rotor circuit to cause the motor to drop in speed and stall at approximately 250 per cent of full-load torque. The results are reported to be very satisfactory from an operating standpoint. It is considered that the protection thus afforded to the pump and mud lines is well worth the additional electrical losses entailed, although oil companies to whom this scheme was suggested several years ago were not then ready to accept the idea, as they hoped that some means could be devised which would have a higher efficiency. Forced ventilation of the motor from a separate motor-driven blower has been resorted to under the circumstances, to prevent overheating during long periods of stalling which may occur.

With this arrangement it should now be possible to successfully compound two induction motor-driven pumps, which has heretofore been considered impracticable.

Automatic Feed

Electric drive has afforded the opportunity for development of means for automatically feeding the drilling bit, and several methods, differing considerably in principle, have been devised. In the differential electric drive, of which there are two types, the rate of feed is balanced against the torque required to turn the drill pipe, so that the feed is automatically regulated to maintain a constant torque. One design of this type of drive makes use of two wound-rotor induction motors which drive the draw works hoist drum and the rotary table through a differential gear unit. Each motor drives one main differential gear of the cluster, and one of the motors also drives the rotary table through suitable gearing. The ring gear of the differential cluster is connected to drive the hoist drum which feeds the bit. The two motors run in opposite directions, so that when they are at the same speed the ring gear and therefore the hoist drum do not turn. Normally the speed of the motor which drives the rotary table is set higher than that of the other motor, and this causes the ring gear and the hoist drum to turn in the direction which will pay out line and thus feed the bit. Any change in torque required to drive the drill pipe will affect the speed of the driving motor and thus increase or decrease the difference between the speeds of the two motors, which consequently changes the speed of the ring gear and the rate of feed correspondingly. Heavy torque will thus slow down the feed to standstill or even reverse it to retrieve the bit, and stalling of the drill pipe will result in instant retrieval until the stalled condition is relieved, after which feeding is automatically resumed.

The two motors are therefore both a power drive and a means of regulation of feed and torque. For hoisting work in removing the drill pipe and bit from the hole, both motors are run in the same direction, thus locking the differential gears, which then merely serve to transmit the power.

In another design of differential drive the power unit, which may be a motor or an engine, drives the ring gear of the differential cluster. One main differential gear drives the rotary table, and the other drives the draw works through a two-speed sprocket and chain transmission. The balance of torque against feed is thus entirely mechanical, and is adjusted by changing the transmission ratio to the hoist drum. With two transmission speeds and three draw works speeds, the total number of adjustments is six, and the speed of the entire drive is regulated by control of the motor or engine.

The action of these two differential drives in controlling the torque and feed is very similar, although the two-motor arrangement provides more flexibility of control. A large number of differential drives has been installed, particularly those of the two-motor type.

During the past few years, methods of obtaining straight holes have been uppermost in the minds of oil company engineers and officials, and thousands of dollars have been spent in endeavoring to determine the causes of crooked holes and methods of preventing them. This has led to the present quite wide acceptance of the theory that the maintenance of proper pressure of the bit on the bottom of the hole is one of the most certain ways of keeping the hole straight. As a result, two somewhat different electrical methods of automatic control of the weight on the bit have recently been developed and put into service.

One of these methods employs electricity only in an auxiliary capacity, but is nevertheless of interest although yet in a developmental stage. It acts on the principle of automatically releasing and setting the draw works brake to feed the bit, but does not provide for its retrieval. In one layout which has been used, which illustrates the principle of operation, the brake lever is attached to the piston rod of a double-acting steam cylinder, and steam is admitted to one side or the other of the piston by solenoid-operated valves, the solenoids being energized by adjustable electric switch contacts opened or closed by hydraulic pressure. The hydraulic pressure which is imparted to this switch is established by a diaphragm which is so attached to a bight in the anchored or "dead" end of the drilling line that the pressure of the diaphragm against the liquid behind it varies with the tension in the line, and hence inversely with the amount of weight resting on the drilling bit. An indicating gage measures the hydraulic pressure.

The position of the contacts in the pressure switch is readily adjusted by turning a button, and they may be placed in a neutral position for any desired pressure. In practise, they are set for as much lower pressure, below that representing the entire weight of the string of tools, as corresponds to the amount of weight desired to be carried on the bit. This closes the contact which causes release of the draw works brake, and the decrease in hydraulic pressure, then resulting from setting part of the weight on bottom, causes the pressure switch to close the other contact and set the brake. This automatic feeding action occurs as frequently as necessary to maintain the weight on the bottom at or above that permitted by the setting of the switch.

The other method is accomplished by equipment entirely independent of the draw works and its drive, and it provides both automatic feed and retrieval. Its main element is an auxiliary induction motor-driven hoist unit, which is installed on the opposite side of the derrick floor from the draw works, or at the side where the calf-wheel is usually placed. The "dead" end of the drilling line is spooled on the hoist drum of this unit. The driving motor is a two-speed wound-rotor induction motor as designed for oil well pumping. It is equipped with a solenoid brake and drives the hoist drum through a transmission gear and a worm-gear reduction unit. The thrust of the worm shaft produced by the tension of the drilling line is carried on a diaphragm which imparts a corresponding pressure to liquid behind it, this being piped to an automatic pressure switch actuated by another diaphragm and functioning to open and close electrical contacts to start, stop and reverse the motor. The hydraulic pressure on this diaphragm in the pressure switch is balanced by air pressure on the other side, established by a small hand pump and regulated by a hand-valve.

As the thrust of the worm shaft is proportional to the weight suspended in the derrick and varies inversely with the amount of this weight set on bottom, the variation in this weight produces a corresponding change in the hydraulic pressure on one side of the switch diaphragm and this results in movement of the diaphragm which actuates the switch. Increase in pressure will cause the switch to start the motor in the direction to feed the bit, while a decrease will result in starting the motor in the reverse direction and thus retrieve the bit. The action of feeding or retrieving reestablishes the required weight on the bit and thus brings the hydraulic pressure back to its original value, when the switch stops the motor and the solenoid brake prevents its coasting.

The amount of weight to be automatically carried on the bit is adjusted by the driller by reducing the air pressure in the switch the necessary amount below that corresponding to the entire weight of the string of tools. The switch functions to set weight on bottom until the hydraulic and air pressures are equalized.

The electrical circuits are so arranged that the two-speed motor runs on its low speed connection for feeding the bit and on its high speed connection for retrieving it.

In field service this equipment functions to maintain a tension in the drilling line varying only about 10 lb. at the drum. The corresponding variation of weight on the bit is determined by the number of lines in the tackle, which is usually from 4 to 10. The actual weight variation is therefore the product of this number by the 10-lb. variation in the tension of the fast line at the drum.

To make this weight control equipment of general utility, electrical control is incorporated to permit the driller to pick the bit up off bottom at any time, or to both feed and retrieve entirely by hand control. By means of a transfer switch, all automatic feed features may be disconnected and the hoist operated from a manual controller for use in rigging-up or for emergency removal of the drill pipe from the hole in case of failure of any part of the draw works or its drive. In this service the motor operates on its high-speed connection. The automatic control feature may also be utilized to maintain and not exceed a predetermined pull on a string of tools or casing which may have become stuck in the hole and perhaps requires all the pull the derrick can withstand to dislodge it.

So far this type of automatic weight control equipment has been used to drill over 16,600 ft. of hole in California oil fields, and very successful results are being obtained.

Rotary Drilling with Direct-Current Equipment

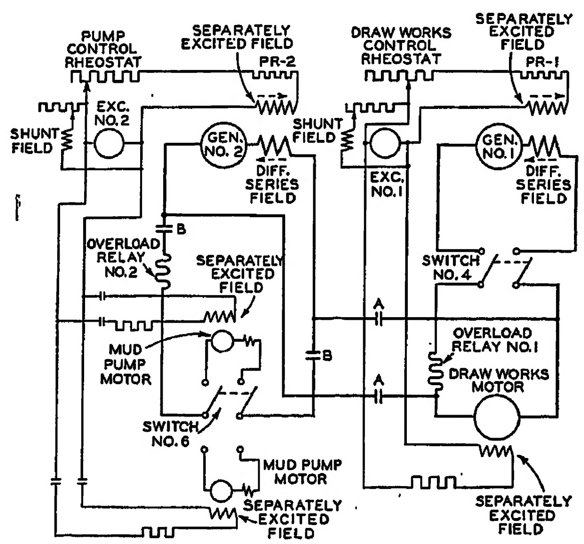
One of the most recent developments in electric drive for rotary drilling and mud pump operation is the application of d-c. motors operated by generator voltage control from engine-driven generators or motor-generator sets. In working out a suitable system, of which two are in successful use, the designing engineers have had recourse to the years of experience gained in applying similar equipment to elevators, electric shovels and steel mill drives, and have been able to make an interesting adaptation to fulfill the unusual requirements of rotary drilling service.

A d-c. rotary drilling equipment usually consists of two or three duplicate generators with direct-connected exciters, driven by duplicate internal combustion engines or by an a-c. motor, one or two motors for driving the draw works, two motors for the mud pumps and suitable control and protective equipment. One generator supplies power to the draw works motor for rotating the drill pipe during drilling, and the other at the same time supplies power to one of the mud pump motors. When it is necessary to withdraw the drill pipe and bit from the hole, the mud pump is shut down and the power from the two generators is combined to supply the heavy demand from the draw works motor.

One of the systems mentioned makes use of differentially compound wound generators, each provided

with a separately excited shunt-wound field opposed by a series field, resulting in a drooping characteristic of the generator voltage with increase in load. One object accomplished by this characteristic is to limit the generator output to the maximum which the engine can deliver, and thus automatically prevent stalling the engine. This also prevents the current exceeding the maximum safe value for the electrical equipment, but permits high torque to be developed by the draw works motor at low speed, and high speed at light loads.

Another object which this generator characteristic accomplishes is to cause the mud pump motor to slow down with increase in load and stall at a maximum torque which does not exceed the strength of the pump. As has already been pointed out, this is the ideal way



	Closed	Open
Drilling	*B*, No. 4, No. 6	*A*
Normal hoisting	*A*, No. 4	*B*
Emergency hoisting with gen. No. 1	*B*, No. 4	*A*
Emergency hoisting with gen. No. 2	*A*	*B*, No. 4

Resistor $P R_1$—$P R_2$ are not used with general shunt fields in series

FIG. 1—ELEMENTARY DIAGRAM FOR D-C. VARIABLE VOLTAGE CONTROL FOR OIL WELL ROTARY DRILLING

Standard arrangement with one draw works motor

to operate the pump. The motor when stalled will not be damaged if it is separately ventilated by a blower, as is customary on the d-c. drilling equipments for the chief purpose of excluding inflammable gases.

The scheme of connections is shown in Fig. 1 for a system with two generators, one draw works motor and two mud pump motors. The positions of the various switches for the several drilling operations are indicated in the legend. For drilling, generator No. 1 supplies power to the draw works motor and generator No. 2 to either of the mud pump motors. For normal hoisting, the generators are in parallel to supply power to the draw works motor, and the mud pump is shut down, while for emergency hoisting, either generator may be used. The arrows in the field circuits show the relative polarity of the separately excited and series fields of the generators.

For the sake of clearness the field transfer connections have been omitted from the diagram, but it should be noted that when the generators are in parallel, their separately excited fields are connected in series, insuring the same degree of excitation to both. When they operate separately, each generator has a block of permanent resistance in its separately excited field circuit equal to the resistance of the field.

It usually is a difficult matter to operate constant voltage d-c. generators in parallel when driven by internal combustion engines, but the differentially wound series fields and the series connection of the separately excited fields result in stable operation and in a division of load approximately in proportion to the generator speeds. Tests on two 75-kw. generators in service showed the respective loads to be 410 and 385 amperes with respective speeds of 1,050 and 975 r. p. m. In all tests where the speeds were the same, the load was evenly divided.

For successful drilling service it is desirable that the engine governors give a speed regulation of 8 per cent or better, and it is necessary that the engines be equipped with flywheels and that their governors have the same characteristics.

Of course this type of drive is not limited to the use of engines as primary power, but may be utilized to full advantage where central station power is available, by the use of synchronous or induction motor drive for the generators. Under these circumstances it would be possible to employ regenerative braking in conjunction with the mechanical brake for lowering pipe, thus reducing the wear on the mechanical brake. This type of electrical braking is impracticable with engine drive, as the only means of absorbing the pump-back power would be by permitting the engines to speed up, which is usually not allowable. However the counter-torque method has been used very successfully on a gas-engine-driven d-c. drilling equipment, by running the draw works motor on the first or second hoisting control point when lowering pipe into the hole. To stop the load, the generator voltage is increased. The mechanical brake is then set when the load comes to rest, and the motor is released.

The curves in Fig. 2 illustrate the volt-ampere characteristic of the differentially compound-wound generator and its relation to the corresponding curve representing the maximum output of the engine. The generator curve does not cross the engine curve; consequently the engine cannot be stalled by any possible load on the generator. This characteristic is fully obtained in actual drilling service.

In Fig. 3 are given the approximate characteristic curves of a 150-hp., 230-volt motor when used with a 175-kw., 1,000 r. p. m. differentially compound-wound generator. The shape of these curves is not only typical for this type of equipment, but is very desirable for

rotary drilling work. It should be noted that the maximum horsepower output of the motor is obtained at the value of current at which the generator curve is tangent to the engine curve, and is therefore the point where the engine is required to develop maximum output. On either side of this point the engine load is lighter.

The curves in Figs. 2 and 3 are characteristic of the mud pump drive as well as the draw works drive. In

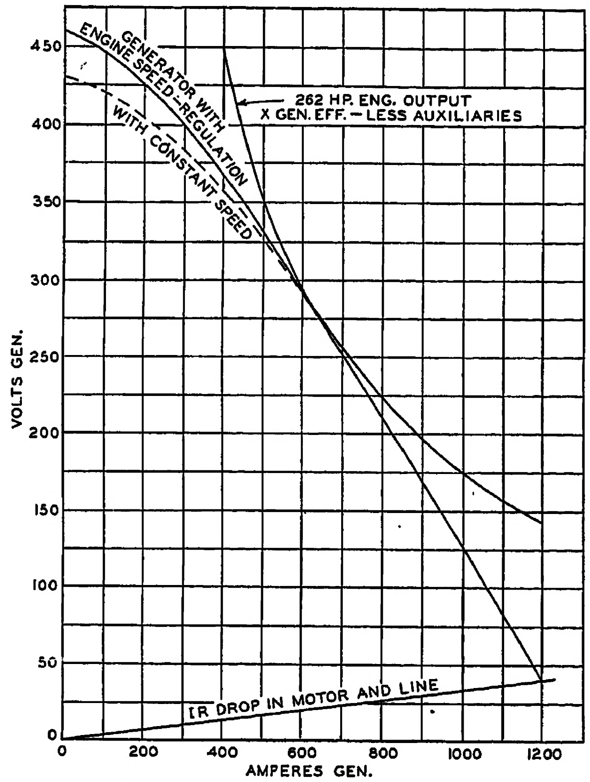


FIG. 2—ESTIMATED GENERATOR CHARACTERISTICS FOR DIFFERENTIALLY COMPOUND WOUND GENERATOR DRIVEN BY INTERNAL COMBUSTION ENGINE

comparison with the speed-ampere curve, which is of the most interest in considering mud pump operation, the volume-pressure curve (curve S) of a steam pump is shown. These curves touch at the point of maximum horsepower output of the pump. The steam pump curve is theoretically a straight line, but there is reason to believe that it actually curves due to throttling, and so very closely follows the curvature of the motor-driven pump characteristic, which of course is due to the effect of saturation in the generator fields. Thus it is evident that with the proper design of generator the d-c. motor-driven pump will equal the steam pump in performance.

In the other system of d-c. drive the practical operation is similar to the one described but the generators used have been shunt wound, separately excited, and the motors compound wound with separate excitation for the shunt winding. When the combined power of the generators is required for hoisting drill pipe, their armatures are connected in series and their separately excited fields in parallel, the two field controllers being mechanically arranged to operate together on corresponding points under this condition.

The series connection of the two generators doubles the line voltage, and hence the draw works motor is designed to operate on 250 volts when working from one generator and 500 volts when working from both. For hoisting conditions with power from both generators, approximately the same range of speed and torque is possible as with the first scheme described.

With the generators operating either singly or in series, increase of the torque load on the motor not only reduces its speed because of its compound winding, but also increases the torque load on the engine. With an engine of suitable size having a drooping speed characteristic at heavy loads, the resulting drop in voltage will reduce the motor speed to the stalling point without stalling the engine.

The economy and flexibility of d-c. drive with power from internal combustion engines will often justify the cost of such equipment, especially for wildcat drilling in remote locations. For instance, this has been found to be the case in the Mississippi delta region, where steam drilling is almost prohibitively expensive, largely due to the difficulty of providing fuel and water. There

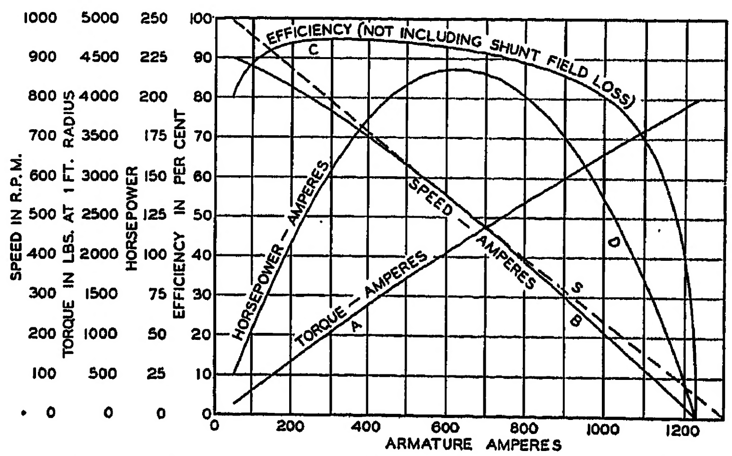


FIG. 3—ESTIMATED CHARACTERISTIC CURVES FOR 150-HP. 450-R. P. M. 230-VOLT SHUNT-WOUND MOTOR, OPERATING FROM GENERATOR WITH CURVE AS IN FIG. 2

the saving effected by the use of a Diesel-electric rig over a steam rig was enough to more than pay for the power plant in the drilling of two wells.

The following is a summary of the advantages of d-c. drilling equipment from the standpoint of the operating engineer.

a. Its characteristics are so designed that it is impossible to impose loads on the engines greater than they can carry, thus definitely preventing their being stalled.

b. It combines the fineness and flexibility of control of d-c. motors with the economy of the internal combustion engine.

c. It has speed characteristics like the steam engine, thus giving a wide range in speed and torque for the draw works and a positive indication of any restriction or stoppage in the mud pump line.

d. It makes available the combined capacity of the mud pump and draw works power supply for heavy hoisting duty when "coming out of" and "going into" the hole.

e. It provides individual control of drilling and mud pump operations, centralizing this control at the driller's stand.

f. It readily provides low table speeds, quick reversals, fast or slow pick-up as required on heavy or light loads, and speeds of the empty hook as high as the crew can handle.

Well Pumping

A wider variety of types of motors is used for well pumping than for drilling, because of the numerous methods of pumping and types of pumping rigs employed, and also because of variable well conditions encountered. A glance at the following items will indicate the many things to be considered in the selection of equipment.

1. Maximum depth of well.
2. Daily production.
3. Gravity of oil.
4. Number of hours pumped.
5. Weight of rods and tubing.
6. Length of stroke.
7. Strokes per minute.
8. Depth of working barrel and fluid level.
9. Amount of sand and gas produced.
10. Percentage of water produced.
11. Frequency of pulling rods and tubing.
12. Accessibility of the well.
13. Straightness of hole.

The majority of wells today are pumped with displacement pumps placed on the bottom end of a string of tubing lowered into the well, with the plunger operated by a string of rods inside the tubing. Oil enters the pump on the down stroke and is lifted toward the surface on the up stroke. On the older type of rigs, the rods are operated by a walking beam driven by a crank and bandwheel, as it is common practise to install this rig on cable-tool drilled wells for drilling and on rotary drills for a stand-by unit. Today this pumping practise is not so prevalent, as many wells are not equipped with bandwheels, and it is therefore necessary to install some form of pumping unit and hoist.

Some wells do not require frequent hoisting of rods and tubing, or "pulling," as it is commonly termed, while others have to be pulled as often as every 10 days. Some operators prefer to have their equipment arranged for both pumping and pulling whereas others desire it only for pumping. The latter then must have a portable pulling outfit which is either gas or electric driven.

No two wells are exactly alike in operating conditions, and the latter may change from week to week or at longer intervals. The fluid level may go down, the gas decrease, water come in, or sometimes the wells sand up. To meet these conditions, it is often necessary to change the stroke, or the speed, or both.

Two-Speed Oil Well Pumping Motors. When motors were first applied to the standard walking-beam type of pumping rig, they replaced steam or gas engines and were required to perform all the operations at the well. The motor had to be fast enough to pull the well and slow enough to pump it, and this resulted in the development of the special double rated, two-speed wound-rotor induction motor which admirably fits these conditions and continues to be a popular drive today, thousands of them being in use. The low speed is used for pumping and the high speed for pulling, bailing, swabbing, and other miscellaneous work at the well. The variable speed feature permits the adjustment of the pumping speed without changing pulleys or gears, and gives proper control of hoisting operations.

This motor is also used advantageously for cable-tool drilling, as has already been mentioned, and serves in this capacity when a light string of tools is used to clean out or deepen a producing well.

The two-speed feature also makes it possible to "shake-up" the well when required to loosen up an accumulation of sand and thus free the valves. This is done by switching the motor to its high-speed connection for a brief period while pumping.

Ratings of these two-speed oil well pumping motors now in use are 35/15, 50/20, 55/25, 65/25, and 75/35 hp., all designed for 6- or 12-pole operation at 440 volts, 50 or 60 cycles. Smaller ratings were at one time popular but operating conditions today call for the heavier equipment.

Squirrel-Cage Motors. The squirrel-cage motor is now used in considerable numbers for well pumping, and is popular because of its low cost and high efficiency. The standard type, the low-starting-current type and the high-starting-torque type all find their field of usefulness for which they are best adapted. Some wells are hard to start and high starting torque is needed, and so the high torque motor is obviously the best. If however as a matter of expediency or availability a normal-torque motor is applied, the well may be started by "rocking" the walking beam if necessary, which requires a reversing switch for the motor. The ratings of motors used run from 7½ to 25 hp., 8 or 10 poles.

In many cases the squirrel-cage pumping motor is connected by chain or V-belt to the shaft of the engine installed at the well, the engine crank being disconnected. The engine is used for pulling the well, and for this purpose the crank is temporarily reconnected and the chain or belt removed. Such an installation requires probably the least investment of any to pump electrically, but a more efficient and compact drive is obtained by employing a small reduction gear unit instead of using the engine shaft, and either installing

a motor large enough for pulling or using a portable hoist equipment for that work.

Some operators prefer not to have many different ratings of motors on each lease, owing to the complication of stock and maintenance problems. However, they appreciate the advantages of high efficiency and power factor, and so to meet their requirements, the Y-delta type of motor is furnished, either of the squirrel-cage or wound-rotor type, usually rated 40/15 or 50/20 hp., 6 or 8 poles. Either the Y or the delta connection is used as the load may require, the advantage of the Y connection being improved efficiency and power factor on light pumping loads. When the starting torque required is considerable, even though the well may be a light pumper, an advantage is gained in starting on the delta connection and running on the Y. This eliminates some of the bad effects of overmotoring in order to obtain sufficient starting torque.

The Y-delta squirrel-cage motor has also been applied for both pumping and pulling, requiring a primary resistor to give a cushioning effect on the first point of hoisting. The second point cuts out this resistance and runs the motor on the Y-connection, giving sufficient torque to handle light loads. The delta connection is used on heavier loads, and is obtained on the third control point. The motor used in this way of course has its limitations in comparison with the two-speed wound-rotor motor, but is somewhat cheaper and more efficient.

Pumping Units. There has been a steady advance in the development of more efficient mechanical equipment for well pumping, encouraged largely by the adaptability of electric drive and the readiness with which the efficiency can be determined by electric power measurements. Compact self-contained electric-driven pumping units of many designs have been developed for wells approximately 5,000 ft. or less in depth. For greater depths such units are less often used owing to their high cost and bulkiness. The horsepower requirements range from 2 to 25 and squirrel-cage motors for full voltage starting are generally used.

One particularly interesting unit of this character recently developed by one of the electrical manufacturers includes a triple reduction gear unit with a crank on the low-speed shaft for operating a walking-beam. The driving motor is a squirrel-cage machine and both the motor and control box are built into and form an integral part of the gear unit. This electrical equipment is of weatherproof construction, and so no housing is necessary. Provision is made for readily changing gears to change the pumping speed. Such an equipment represents the maximum in simplicity and the minimum in installation work.

Some pumping units have some flywheel effect or are equipped with small flywheels, and for these the high-resistance rotor type of squirrel-cage motor is theoretically best adapted, although there is a question whether under well pumping conditions there is any decrease in power consumption. The motor efficiency is of course lower than that of a normal design of squirrel-cage motor, but the current peaks on the pumping cycle are reduced, and the motor may thus run on a better point of the efficiency curve. Any gain which might thus be possible in reducing the size of motor required is usually opposed by the preference of most operators for a larger motor than initial pumping conditions require to provide for the fact that a year or two later the load is likely to increase as the level of fluid in the well subsides, the gas decreases, or water encroachment increases.

Reduction Gear Units. The old standard pumping rig with belted bandwheel to drive the crankshaft is inefficient at best and the bandwheel and belts are now quite often replaced by single- or double-reduction gear units with a crank on the low-speed shaft. This has not materially affected the application of electric drive but has been brought about by the desire and necessity for better equipment to meet modern conditions. Electric drive has made it possible to detect the source of losses in the old equipment and is thus in a way considerably responsible for these improvements. Provision is made on these gear units to drive a tubing hoist for pulling operations.

Such an arrangement is now frequently used to drive the calf-wheel for a stand-by hoist on a rotary drilling rig, and is usually equipped with a two-speed pumping motor. When the well is completed, this equipment is left installed at the same location for pumping the well, the tubing hoist and a walking beam being added, as well as a good mechanical counter-balance for the crank or beam.

Central Power Jacks. Provided the terrain permits, the pumping of small producers, usually shallow wells, is accomplished in groups from a central plant, called a "power," when it becomes uneconomical to pump them individually. The central power consists of one or more large eccentrics on a vertical shaft, the collar of the eccentric being attached to rods which extend to the wells and pump them by bell-cranks called pumping jacks. The central power shaft is engine- or motor-driven. As many as 20 or 25 wells are thus pumped from one plant. Hook-ups of 10 to 25 wells require approximately 35 to 40 hp., but as the conditions vary larger motors are often used, from 40 to 75 hp. in some cases. The starting torque is usually heavy and may be obtained with a high-torque squirrel-cage motor, but is sometimes done by overmotoring. Constant-speed wound-rotor motors are used if there is no friction clutch on the rig, as slow starting is usually a necessary practise to avoid rod breakage.

Control Units

One of the rather unique developments in oil field electrification is the assembly of all control apparatus for a motor on welded structural steel or pipe framework at the factory, where it is completely wired before ship-

ment. This practise has been applied to drilling equipments, which must of necessity be frequently moved from one location to another, and to the two-speed pumping motor equipments, which include several items of control apparatus. The resulting advantages to the user are obvious, and are particularly important in an industry involving the difficult conditions of operation as encountered in the production of oil. The frameworks for these units are sturdily constructed to withstand abusive handling, and mounted on skids to facilitate frequent moving.

Protected Equipment

In many installations of pumping equipment, no house is provided. Open type motors are usually covered with a small sheet metal "dog house," but the totally enclosed fan-cooled type of motor is becoming more popular.

There is a demand for a reasonable amount of protection of the electrical equipment against hazardous gas conditions, particularly for drilling equipments where gas is more likely to be prevalent. Motors of the open type are usually acceptable to the oil companies but collector rings are specially enclosed by a suitable housing. Electrical contacts of the control apparatus are immersed in oil or are built in an enclosure specially designed for the purpose. In general, the design of such enclosures follows the recommendations of the U. S. Bureau of Mines for equipment permissible for use in gaseous mines, or of the Underwriters Laboratories for equipment to operate in Class 1, Group D hazardous conditions.

Where it is possible, as on drilling rigs, to set the control apparatus back at a safe distance from the well, this is sometimes done and standard equipment is then employed.

Another method of protection which has been applied to both motors and control is to enclose them suitably and ventilate the enclosures with fresh air from a separate blower, the air being piped from a sufficiently distant point to be free from hazardous quantities of gas. This method is a good one for magnetic control equipments, which, if oil immersed, are considerably more expensive and give less satisfactory service on heavy duty.

Air-Gas Lift

When wells stop natural flowing, many of them can be made to flow artificially by compressed air or air forced down between the casing and tubing. The compressors are usually driven by squirrel-cage motors, 75 to 200 hp., 8 poles, with close coupled belt drive. Hand starting compensators are generally used although, due to gaseous conditions, magnetic compensators placed in a separate building are often preferred. An oil immersed push button is located near the motor. Synchronous motors are being considered more and more for this service, due to penalty and bonus clauses in central station power rates. Intermittent blowing is quite popular in certain fields and this is easily accomplished by an electric timer and electric solenoid valves. Frequently the valve controlling the flow of gas freezes up with ice due to the expansion of the gas and electrically heated valves have solved the problem.

Conclusion

Though the petroleum industry still relies largely on engine power, great strides have been made during the past ten years in the development and application of electrical apparatus and in the extension of central station power in the fields, and oil companies are giving an increasing amount of attention to its use. There are many other uses for electricity in oil production, such as for gathering and pipe line pumps, welding, dehydration, illumination, heating and refining, but these are beyond the scope of this paper.

Acknowledgments

The published works of others in the electrical and petroleum industries have been consulted for data and facts in the preparation of this paper, including papers or articles by Messrs. H. E. Dralle and L. J. Murphy of the Westinghouse Electric and Mfg. Company, Thomas Fleming, Jr., of the Oil Well Supply Company, B. L. Moore of the Humble Oil and Refining Company, and O. B. Goldman of The Drillometer Company. Unpublished papers also consulted include one on "The Practical Application of Electricity to Rotary Drilling," by Mr. W. H. Skivington, Electrical Engineer of the Doheny-Stone Drill Company, several by Messrs. W. G. Taylor and B. M. Mills of the Industrial Engineering Dept., General Electric Company, and one read before the Pacific Coast Electrical Bureau by Mr. J. H. Fenton of the Westinghouse Electric and Manufacturing Company. To all of these the authors of the present paper are indebted for information, as well as to the Westinghouse Electric and Mfg. Company for permission to include material concerning a recent development not previously announced.

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Discussion

David Hall: The paper calls attention to the fact that the oil industry is only 7 per cent electrified, which fact cannot be attributed in any measure to the inadequacy of electric power, but rather to the "inertia" of steam practise, the familiarity of operators with steam, and to the lower initial cost of steam equipment. Builders of steam machinery have jealously noted any introductions of electric power and have met electrical competition by larger engines and higher steam pressures and it is probable that the introduction of electricity in the oil fields has hastened the improvements in steam machinery.

This evolution is still progressing and the paper refers to recent accomplishments in mud pump drive, the results of which have not yet been published. This drive, which was introduced by the Westinghouse Electric & Manufacturing Co. and tried out through the cooperation of one of the large oil companies in Southern California, consists of wound rotor induction motors with permanent resistance and reactance in the rotor circuit. The real reason for this arrangement is to provide a prime mover which will slow down under increasing loads and actually stall before any injury is done to the pumps. This arrangement successfully operates pump, singly or in tandem, or in parallel and the entire equipment permits of stalling and the maintaining of the stalled torque for operations when low speed and high pressures are necessary.

The use of permanent resistance in the rotor with the necessary losses may provoke criticism if the equipment is narrowly viewed, but a broader vision of the over-all efficiency will clarify this question. For example, the normal cost of operating a full drilling outfit is roughly $600 for twenty-four hours. If electrically equipped the cost of power will not exceed $20 or $30 per day, of which $2 per day might be charged to the resistance, without which the entire operation would be less safe.

Rotary Drilling. The paper has given a concise résumé of rotary drilling, which is the universal method used in California. As an example of progress it might be mentioned that the deepest well in the world, drilled to a depth of 10,030 ft. in the Ventura district, uses a completely electrified rig of the Hild differential type, and two motors as described in the paper.

The drilling equipment was supplied with two 25/65-hp. motors having a total pull-out torque equivalent to approximately 600 hp. In this differential drilling arrangement, the full power of both motors is available for either drilling or hoisting.

As a further example of the increased demands for more power for drilling these deep holes and the desire for faster drilling, single-motor sizes have been increased from 50 hp., as of less than ten years ago, to the present *Y*-delta equipment referred to in the paper and it is well to note that this equipment has an even greater maximum torque capacity than the 600 hp. mentioned above.

Direct Current. Our reason for introducing direct current in the oil fields was to meet a demand for the use of electricity in the drilling of wildcat wells. Since the electric power must be generated at the well site, the simplest and most flexible equipment could be made with direct current.

The first equipment was set up in the Los Angeles district, particularly for close observation, and after successfully drilling three wells, it was moved to an isolated district in Colorado, where it is now in use. The success of this equipment has been followed by the sale of additional equipments and the problem of wildcat drilling has been demonstrated. The use of such equipment will probably be expanded as the economies of this method become more generally known.

The authors have not only pointed out the use of electricity in drilling but have called attention to the problem of pumping. This problem is demanding more attention probably than any other in the oil fields. Much total power is involved on account of the many wells, some 350,000 now active, and efficiency is a major concern. Numerous schemes have been devised and many are on trial; the final answer is not in sight and the great depths now encountered have increased the difficulties and interest in this subject.

F. E. Terman: I would inquire as to whether any serious efforts have been made to develop electrical pumps in which the motors can be dropped down into the casing. In the case of deep wells I understand that the gas pressure is relied upon to lift the oil part way to the surface, and that the pumping methods now employed will not satisfactorily pump the well if the gas pressure fails. This is because the stretch and inertia of the pumping rods are such that when the length is in the order of two miles impulses applied by a motor at the surface must be considered as traveling by wave propagation, and this introduces many complications. I have heard that several attempts have been made to develop some sort of a centrifugal pump and motor unit that could be dropped down the well casing, and would appreciate hearing a discussion of the merits and disadvantages of such pumps, and whether there is any serious effort now being made toward the development of such equipment.

H. C. Hill and J. B. SeLegue: As far as submersible motors are concerned, a number of attempts has been made to solve this problem in order to produce a more efficient method of pumping and one which could operate on crooked holes and at great depths. These experiments have been along the line of centrifugal pumps as well as reciprocating pumps but it is the opinion of the writers that although some success has been obtained in wells to a depth of 3,000 ft., it is not practical as yet to pump wells of 7,000 ft. or more by this method. In the first place, the smallest motor so far constructed has an outside diameter to fit in a 6⅝ in. casing and this of course would not fit in the bottom of some of the deeper holes. It is also very difficult to seal the motor so that it will not absorb moisture at the tremendous pressures which are encountered. Furthermore, the cable to conduct the power from the surface to the motor is very expensive, difficult to handle, and not of long life. There are very few of these submersible pumps in operation in the oil industry although several of them have been used in water well pumping of shallow depths. More experience has been had on these in the mid-continent field than in the California field but we understand that very few of them have been used over 2,000 ft. in depth.

More detailed description of the design and operation, as well as some of the results obtained is contained in an article by E. S. Haury, page 126, of the 1931 issue of the *Petroleum Engineer Handbook* published by the Petroleum World. It might be interesting at this point to add that as far as pumping with sucker rods at great depths is concerned, satisfactory results have been obtained in wells at Santa Fe Springs with the pump located 7,801 ft. from the surface. This matter is covered in an article by Mr. B. H. Robinson in the proceedings of the Twelfth Annual Meeting of the American Petroleum Institute, November, 1931

Calorimeter Measurement of Stray-Load Losses of a 55,000-Kva. Generator
Having Enclosed System of Ventilation

BY G. D. FLOYD*
Member, A. I. E. E.

and

J. R. DUNBAR†
Member, A. I. E. E.

Synopsis.—The paper covers a number of thermal or calorimeter tests which were made on a 55,000-kva. generator at the Queenston generating station of the Hydro-Electric Power Commission of Ontario. The objects of the tests were to determine stray-load losses on short circuit and under rated load, and to obtain some information regarding the accuracy of this type of test. The paper includes descriptions of the methods followed and of the actual tests made. The details of the calculations are given in the appendix.

The results of the tests show that the stray-load losses can be determined with fair accuracy by this method on large units when an enclosed system of ventilation is used. They also seem to show that the difference between the stray-load losses under load conditions and under short-circuit conditions is slight, and that a test under load conditions is justified only when a very accurate determination of the losses is required. For most purposes, a test under short-circuit conditions seems to be sufficient.

Introduction

This paper covers a number of thermal or calorimeter tests which were made on a large hydraulic turbine-driven electric generator at the Queenston generating station of the Hydro-Electric Power Commission of Ontario. The primary object of the tests was to determine stray-load losses on short circuit and under rated load, and information was also desired on the accuracy of this method of determining the stray-load losses.

Description of Unit

The generator tested is known as No. 10 unit. The nominal rating of this machine is 55,000 kva., 12,000 volts, 80 per cent power factor, three-phase, 25-cycle, 187½ r. p. m. It is practically a duplicate of the 45,000-kva. units that have been previously described.[1]

The tenth unit differs from the preceding ones in that it has a closed ventilating system. Fig. 1 shows, in diagrammatic form, the ventilating arrangement of the first machines installed. The air is drawn in through a duct, either from the outside or from the generator room. After passing through the windings and core it is discharged through the generator frame into an enclosure between two floors of the power house. It is then discharged to the roof of the power house through exhaust fans, or if it is desired, the air can be recirculated to heat the generator room. A diaphragm is located across the wheel pit just below the generator coupling for the purpose of keeping the ventilating air clear of the turbine floor.

Fig. 2 shows, diagrammatically, the ventilating arrangement used on No. 10 unit. It will be noticed that the ventilating system of the new unit is completely closed. The heated air discharged from the unit passes through two air coolers each having a water requirement of 250 gallons per min. with cooling water at 20 deg. cent. The two coolers will absorb 1,090 kw. from the air, with a rated air flow of 115,000 cu. ft. per min.

Calculated Loss Data

It is possible to calculate the losses of a synchronous machine with a very close degree of accuracy. The only losses about which there is any great uncertainty are those defined in the A. I. E. E. Standards as the stray-load losses.

Several writers[2,5,6,7,8,9] have attempted to develop methods for calculating these losses but, as far as the writers know, no complete determination has been published. Eddy current losses in the armature copper can be calculated with a fair amount of accuracy but the extra iron losses are practically impossible of calculation.

In Holmes'[4] paper it is shown that the armature eddy current loss was of the order of 50 per cent of the total stray-load losses in a certain machine. Since the loss that can be readily calculated is such a small percentage of the stray-load losses, the practical method of determining them before the machine is tested is to compare the machine with others of similar construction that have been tested, and to estimate the stray-load losses from the test data on the previous machines.

The calculated ratio of the a-c. resistance to the d-c. resistance, following Gilman's method,[8] was as follows:

Top coil side	1.16
Bottom coil side	1.08
Average for winding	1.12

A comparison with tests on other similar machines indicated that the total stray-load losses would be approximately five to six times the eddy current loss in the armature copper. Since the calculated value of armature $I^2 R$ loss at 75 deg. cent. was 205 kw. the

*Assistant Engineer, Hydro-Electric Power Commission of Ontario, Toronto, Ontario.

†Electrical Engineer, Canadian Westinghouse Company Limited, Hamilton, Ontario.

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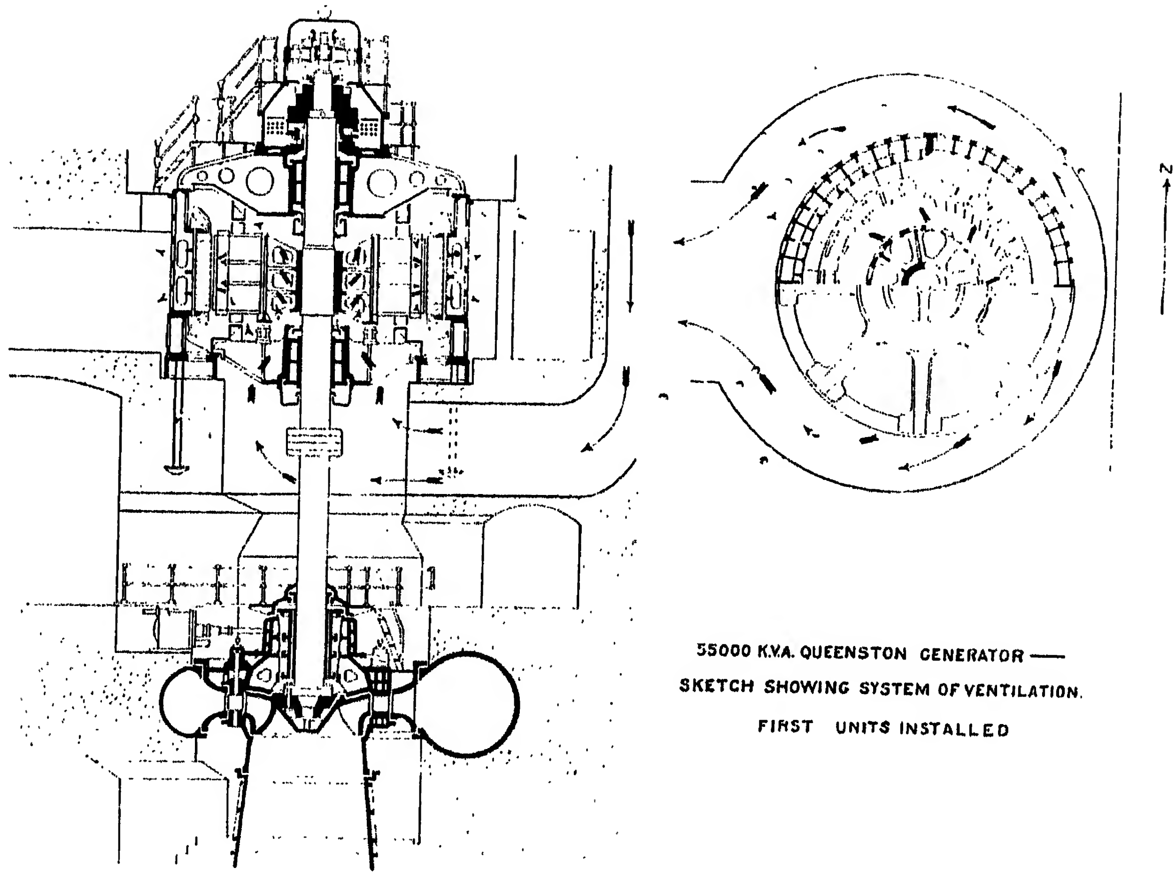

FIG. 1—DIAGRAM TO ILLUSTRATE VENTILATING ARRANGEMENTS OF FIRST UNITS INSTALLED AT QUEENSTON

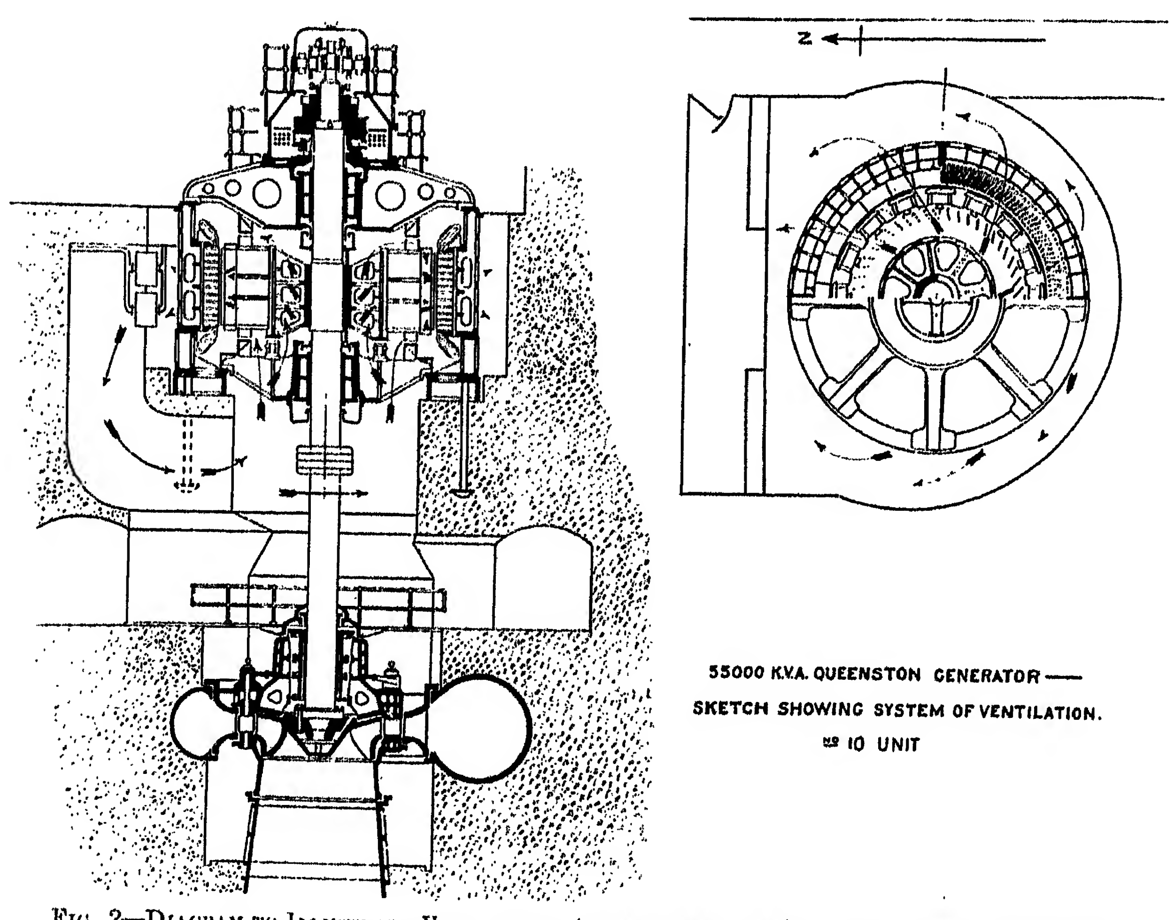

FIG. 2—DIAGRAM TO ILLUSTRATE VENTILATING ARRANGEMENTS OF NO. 10 UNIT AT QUEENSTON

armature eddy current loss would be approximately 25 kw. and the total stray-load losses between 125 and 150 kw. As the A. I. E. E. Standards at the present time recognize only the determination of stray-load losses with the machine short-circuited, the above estimated losses are based on such tests.

Method of Tests

The general method followed in making the tests was to operate the unit under a number of conditions until the temperature of the cooling air, stator iron, and stator copper became constant, great care being taken to measure these quantities, especially the temperature of cooling air, very accurately. As the accuracy of this type of test depends on a very accurate measurement of the temperature of ingoing and outgoing air on each of the tests, a number of high grade thermometers calibrated and graduated to 0.2 deg. cent. was used. Ten of the thermometers were used on the outgoing air from the generator placed at the point where this air enters the cooler. Ten thermometers were also used to measure the temperature of the air at the point where it leaves the cooler. Eight thermometers was placed on the stator iron, one on the top iron and one on the bottom iron, equally spaced around the periphery. Thermometers were also placed on the steel wall of the chamber enclosing the unit, and in the air outside this chamber. A number of thermometers was placed in the inlet air ducts to the unit to determine if there was any drop in temperature after the air had left the cooler. Twenty-four thermocouples located in the stator slots were read during the tests, the average of these 24 detectors being taken as the temperature of the stator copper.

Electrical readings of current, voltage, and power were all taken with portable meters of good accuracy. It should be clearly understood, however, that all these tests were made in the field, and although every effort was made to hold the electrical quantities as nearly constant as possible, this could not always be done. The variations were, in most cases, small, but, as will be noted later, when the short-circuit thermal test was made it was found that the stator current had increased considerably before being corrected, and this introduced an inaccuracy in the temperature reading, which however practically corrected itself after an adjustment of the current was made.

Test Data

The following data had been obtained when the acceptance tests were made on the unit. The friction and windage and core loss were determined by the retardation method.[10]

Friction and windage	215 kw.
Core loss at 12,000 volts	355 kw.
Stator resistance, T-T, at 75 deg. cent.	0.0197 ohms.
Rotor resistance at 75 deg. cent.	0.341 ohms.

The estimated friction loss in the bearings was approximately 65 kw.

Tests

The following tests were made:

Test No. 1—Windage Test.

For this test, the unit was operated for 9½ hours at synchronous speed without excitation. Temperatures were then read for 2½ hours at ½-hour intervals. At this time the test was discontinued, as the time available for the other tests proposed had become limited. Although the temperature rise of the air was almost constant the unit had apparently not come to complete thermal equilibrium. Accordingly, the results of this test were discarded and the test repeated later.

When the test was repeated the unit was operated at

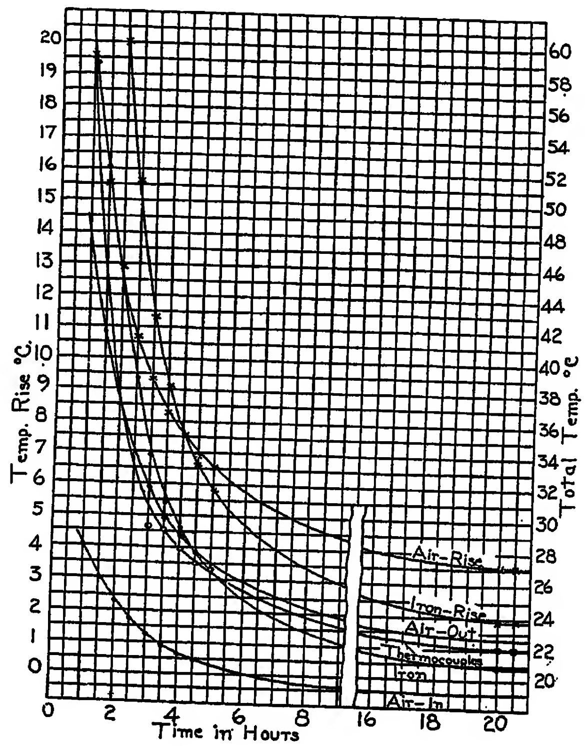

Fig. 3—Cooling Curves—Test No. 1—Windage Only

synchronous speed without excitation for 20½ hours. Readings of temperatures were taken during the first part of the cooling cycle for a period of 5 hours, and two readings of temperatures were taken at the end of the cooling period. The results of this test are shown in Fig. 3. The temperature rise on windage was slightly lower than that obtained on the first test.

Test No. 2—Core Loss.

The unit was operated at synchronous speed with sufficient excitation to give 12 kv. at its terminals. The results of this test are shown in Fig. 4.

The results of this test are very consistent, and indicate that the temperatures of the unit and the temperature rise on the air can be found very accurately,

although the test must be continued for a sufficient length of time to allow the temperatures of all parts of the unit to reach a constant value. It will be noted that the temperature of ingoing air to the unit rises along with temperature of the unit itself; air, iron, and copper temperature arriving at a constant condition at the same time.

Test No. 3—Short-Circuit Test.

On this test the unit was operated at its rated current of 2,650 amperes under three-phase short circuit. The results of this test are shown in Fig. 5.

It was found difficult to hold the stator current constant on the unit, as it has a direct-connected shunt wound exciter, so that small variations in the speed caused a corresponding variation in the excitation and a change in the value of current. No special arrangements were made to control the excitation of the unit, and it is believed the accuracy of the test could be increased by a small degree if this had been done.

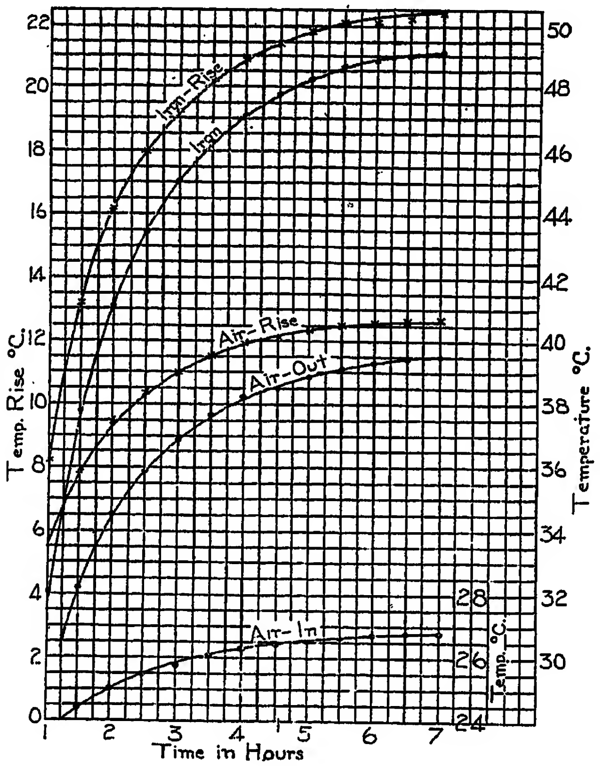

Fig. 4—Heating Curves—Test No. 2—Core Loss and Windage

Terminal voltage.......12,000 volts
Field current........... 314 amperes
Collector ring voltage... 98 volts

Test No. 4—Test at Rated Load.

This test was made in two parts, Test No. 4(a) with a water rate of 500 gallons per minute through the coolers and with rated load on the unit, and Test No. 4(b) with a water rate of 400 gallons per minute with the same load as on the previous test. In order to complete the test in a minimum time, the unit was operated for 8 hours at approximately rated load during which no temperature readings were taken. The load was then set accurately as close to rated conditions of load, power factor, and voltage as could be obtained and held at this value. Temperature readings were taken over a period of 3 hours at ½-hour intervals. The water rate was then adjusted to 400 gallons per minute, and temperature readings taken for 4½ hours at ½-hour intervals. The results of this test are shown in Fig. 6.

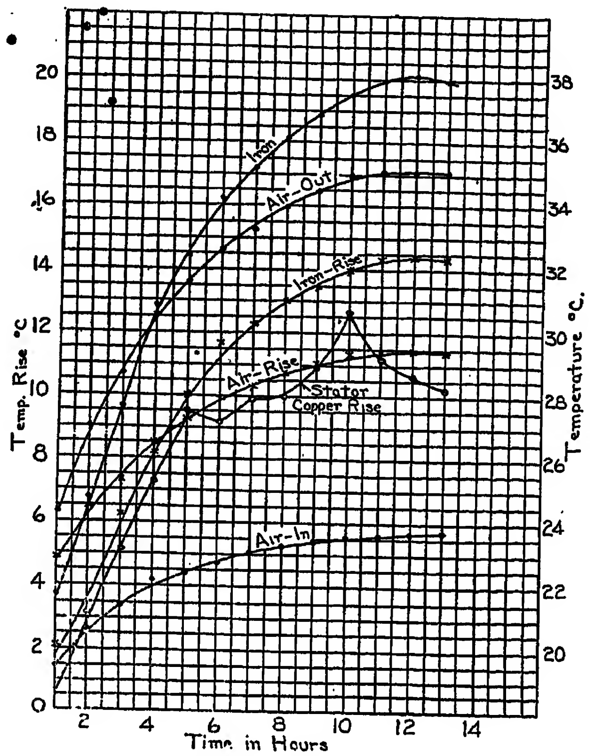

Fig. 5—Heating Curves—Test No. 3—Short-Circuit Loss and Windage

Armature current........2,650 amperes
Field current............ 320 amperes
Collector ring voltage.... 98 volts

This test indicates the accuracy with which the temperature measurements were made, and the effect of changing the water rate through the coolers. It will be noted that immediately following the adjustment of water rate, changes in temperature occurred which although not great, were quite definite, and a period of 4½ hours was required to bring the unit back to new constant temperatures differing from the previous ones by approximately 1½ degrees. The temperature rise of the air and on the iron, however, returned to the same values which they had had with a water rate of 500 gallons per min.

Results of Tests

The stray-load losses are determined by the difference between the total losses as calculated from the temperature rise of the air, and the known losses. The actual steps in the calculation of the stray-load losses are given in detail in the appendix.

The following is the method used in working up the results:

The first test gives the temperature rise on windage only. The second test gives the rise due to windage and core loss. The difference between these two temperature rises gives the rise due to core loss only. Since the core loss is known from other tests, a constant K may be calculated giving the kilowatt loss per degree rise. The kilowatt loss may then be determined for any other operating condition, from the air rise.

These calculations involve the following assumption:

In an enclosed ventilating system, where heat is being generated at a constant rate and the air is being cooled in coolers using a constant flow of cooling water, the kilowatts converted into heat are proportional to the temperature rise of the air, after all conditions have become constant.

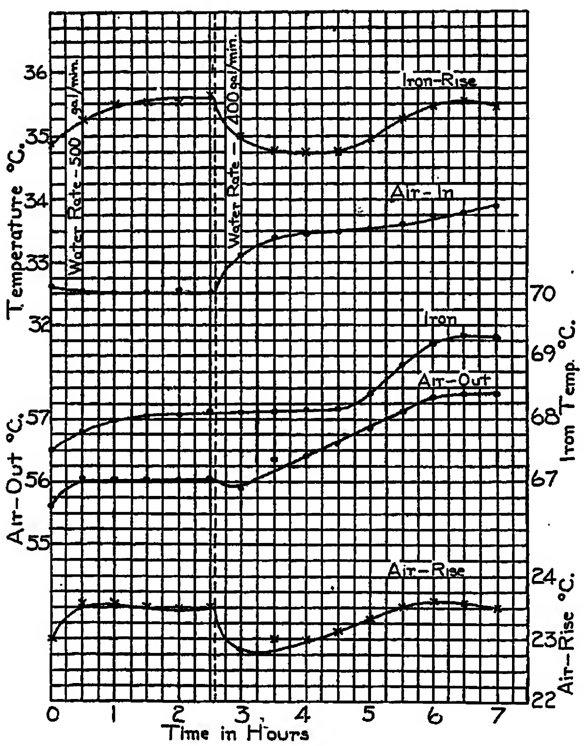

Fig. 6—Heating Curves—Test No. 4—Rated Load Tests

	1st Period	2nd Period
Water rate	500 gal. per min.	400 gal. per min.
Armature current	2,580 amperes	2,610 amperes
Terminal voltage	12,070 volts	11,900 volts
Kw. load	43,400 kw.	43,200 kw.
Field current	608 amperes	612 amperes
Collector ring voltage	229 volts	234 volts

It is readily seen that the crux of the method is that all conditions must be constant. Among other things, this requires that the humidity and barometric pressure must not change during a series of tests. If the barometer were to drop appreciably during a series of tests, the constant K would be affected, and it would be necessary to repeat the "windage only" and the "windage and core loss" tests, in order to obtain reliable results. Also, a constant K, determined under certain atmospheric conditions, cannot be used with the results of tests under different atmospheric conditions.

The following are the losses, as computed from the tests.

Test No. 1	Windage	152 kw.
Test No. 2	Windage + core loss	538 kw.
Test No. 3	Total losses on short circuit	483 kw.
	Stray-load losses, by difference	108 kw.
Test No. 4	Total losses under load conditions	990 kw.
	Stray-load losses, by difference	138 kw.

A check on these losses was obtained from the heat absorbed by the cooling water.

The details of the calculations are shown in the appendix. The following are the results:

Test No. 2	Heat absorbed by cooling water =	475 kw.
Test No. 3	Heat absorbed by cooling water =	475 kw.
Test No. 4(a)	Heat absorbed by cooling water =	1,030 kw.
Test No. 4(b)	Heat absorbed by cooling water =	1,010 kw.

These figures are remarkably close to the figures obtained from the air rise, when it is remembered that the thermometers used in the cooling water were read to the nearest half degree only.

The generator has a plate shell surrounding it, and an attempt was made to determine the amount of heat lost from this shell during the various tests. The temperature of the shell and the temperature of the surrounding air were determined and the radiation loss calculated as shown in the appendix. The following are the values of the radiation losses, as calculated.

Test No. 1	None
Test No. 2	7 kw.
Test No. 3	4 kw.
Test No. 4	16 kw.

A recalculation was made, allowing for the above radiation losses, which is shown in detail in the appendix. The following are the results.

Test No. 1	Windage	149 kw.
Test No. 2	Windage + core loss	535 kw.
Test No. 3	Total loss	479 kw.
	Stray-load losses	104 kw.
Test No. 4	Total loss	987 kw.
	Stray-load losses	135 kw.

This calculation indicates that the radiation loss makes a very small difference in the stray-load loss measured by this test. It is probably less than the experimental error associated with the type of test.

Bearing friction gives a further remarkably close check, as follows:

Friction and windage loss, retardation test	215 kw.
Windage loss, calorimeter test	152 kw.
Friction loss, by difference	63 kw.
Estimated friction loss	65 kw.

Conclusion

The results of this test indicate that, for this particular type of unit, the stray-load losses under short circuit and at rated load are approximately equal.

The stray-load losses are about 50 per cent of the stator copper loss at rated load. The results also indicate that if sufficient care is taken in the measurements of temperatures, the stray-load losses can be determined with fair accuracy on large units when an enclosed system of ventilation is used. The great drawback appears to be the time necessary to make a complete series of tests, although it is possible that a compromise test over a short period of time may be made and the final temperature rise of the air determined by calculation.

The difference between the stray-load losses under load conditons and under short-circuit conditions is slight, but these tests seem to show that the losses under load conditions are a little higher than those determined under short-circuit conditions.

The results obtained by Laffoon and Calvert[11] by calorimeter tests on turbo-generators also show the stray-load losses under load conditions to be slightly higher. In other words, if an accurate determination of the losses is required, a test under load conditions is justified, but for most purposes, a test under short-circuit conditions seems to be sufficient.

Appendix

Calculations

For the benefit of those who wish to check the calculations in detail, the actual figures are given here.

1. To Determine Constant K

Test No. 1
Temperature rise due to windage = 3.6 deg. cent.

Test No. 2
Temperature rise due to windage + core loss = 12.75 deg. cent.
Temperature rise due to core loss only = 9.15 deg. cent.

Core loss = 355 kw.
Field copper loss = 31 kw.

Total loss heating air 386 kw.
Constant K = kw. per deg. cent. rise = 42.19

2. To Determine Total Losses

Test No. 1	Temperature rise = 3.6 deg. cent.	Total loss = 152 kw.
Test No. 2	Temperature rise = 12.75 deg. cent.	Total loss = 538 kw.
Test No. 3	Temperature rise = 11.45 deg. cent.	Total loss = 483 kw.
Test No. 4	Temperature rise = 23.5 deg. cent.	Total loss = 990 kw.

3. To Determine Stray-Load Losses, by Difference

Test No. 3
Total loss = 483 kw.
Windage loss = 152 kw.
Field copper = 31 kw.
Stator copper = 192 kw.

Total, by summation = 375 kw.

Stray-load losses, by difference... 108 kw.

Test No. 4
Total loss = 990 kw.
Core loss = 355 kw.
Windage = 152 kw.
Field copper = 145 kw.
Stator copper = 200 kw.

Total, by summation............ 852 kw.

Stray-load losses, by difference... 138 kw.

Cooling Water Check

500 Gallons of water per minute
= 5,000 lb. per minute
= 5,000 × 0.4536 = 2,268. Kg. per min.
1 kg. calories = 4.186 kw-sec.

Therefore 1 deg. cent. rise in 500 gals. of water per minute is caused by 2,268 kg. calories per minute, or by

$$\frac{2268}{60} \times 4.186 = 158.2 \text{ kw.}$$

Test No. 2 and Test No. 3

Water rate = 500 gallons per minute.
Rise of cooling water = 3 deg. cent.
Hence, heat abstracted = 3 × 158.2 = 475 kw.

Test No. 4 (a)

Water rate = 500 gallons per minute.
Rise of cooling water = 6.5 deg. cent.
Heat abstracted = 6.5 × 158.2 = 1030 kw.

Test No. 4 (b)

Water rate = 400 gallons per minute.
Rise of cooling water = 8 deg. cent.
Heat abstracted = 8 × 0.8 × 158.2 = 1010 kw.

Radiation Loss

Radiation constant = 1.77 B. t. u. per hr. per deg. fahr.
Radiating surface = 1,140 sq. ft.
Radiation from complete casing per deg. cent.

$$= \frac{1.77 \times 1140 \times 1054 \times 1.8}{3600 \times 1000} = 1.063 \text{ kw.}$$

Test No. 2

Temperature difference between shell and surrounding air = 6.5 deg. cent.
Radiation loss = 6.5 × 1.063 = 7 kw.

Test No. 3

Temperature difference = 3.8 deg. cent.
Radiation loss = 3.8 × 1.063 = 4 kw.

Test No. 4

Temperature difference = 14 deg. cent.
Radiation loss = 14 × 1.063 = 15 kw.

Recalculation, Allowing for Radiation

1. To Determine Constant K

Temperature rise due to core loss only = 9.15 deg. cent.
Kw. core loss + field loss = 386 kw.
Radiation loss = 7 kw.
Loss heating air = 379 kw.
Constant K = 41.4

2. To Determine Total Losses

Test No.	Temp. rise	K × temp.-rise	Radiation loss	Total loss
1	3.6° C.	149	0	149
2	12.75° C.	528	7	535
3	11.45° C.	475	4	479
4	23.5° C.	972	15	987

3. To Determine Stray-Load Losses, by Difference

Test No. 3	Total losses	479
	Losses, by summation	375
	Stray-load losses	104
Test No. 4	Total losses	987
	Losses, by summation	852
	Stray-load losses	135

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This bibliography is not complete. For further references see bibliographies included in the papers mentioned.

Discussion

E. A. Crellin and F. I. Lawson: During recent years more and more attention is being directed to the matter of waterwheel efficiencies. Since the only practical method of determining the efficiency of a modern prime mover is by calibrating the generator as a dynamometer and carefully measuring its output while it is assuming the power system load, hence the accuracy of hydro unit efficiency tests depends on the accuracy of the generator calibration.

Most generator losses can be determined with refinements well within the range of accuracy of the hydraulic input measurements. Stray load losses, however, fall into the classification of residual losses which cannot be readily isolated. Following the best information available the Institute has set up rules for the allocation of stray load loss based on measurements made under the very low magnetic density existing in the machine during a steady short-circuit state. This has often aroused the natural inquiry as to whether or not such a determination completely includes all the losses which may be present during load conditions involving much higher and differently distributed magnetic densities. The fact that the Institute rules concerning this point have been changed within comparatively recent years to recognize higher losses bears witness to the uncertainty regarding these stray load losses.

For these reasons the information presented by the authors, giving an independent determination of stray load losses, is a distinct contribution to the hydraulic as well as the electrical engineer.

Within the past eight or nine years efficiency tests have been made on quite a number of hydroelectric units on the Pacific Gas and Electric system. The following tabulation of generator losses obtained by the retardation method during some of these tests may be of interest.

The Stanislaus unit has been used during recent years as somewhat of a proving ground for waterwheel buckets. Tests on the unit when equipped with different types of buckets on the two

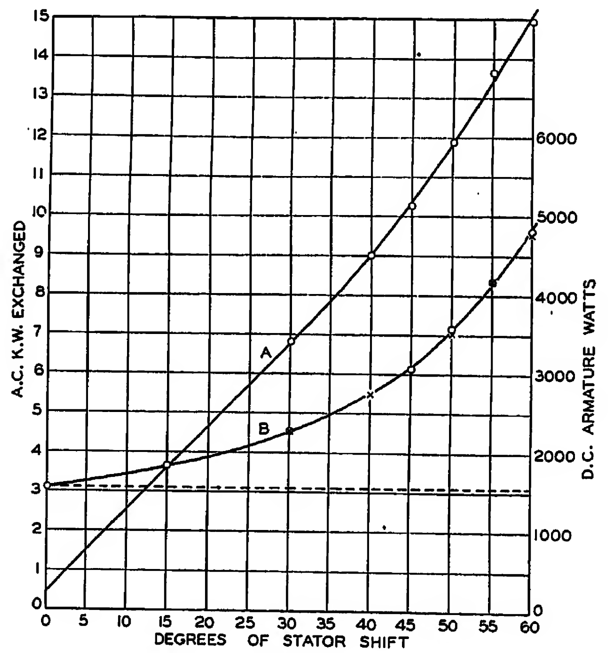

FIG. 1

Curve A—Kw. exchanged at 100 per cent power factor—200 volts
Curve B—D-c. armature watts (o) and sum of losses (x)

overhung wheels could not be verified by tests using each wheel singly. The single wheel tests of course involve half load on the generator for full load on the wheel, whereas when using both wheels the loading becomes complete on the generator as well as the wheels. Since the generator is of a rather early design (1907) and was later rebuilt for a higher rating, its stray load losses under full load conditions come under suspicion as an uncertain factor.

In an attempt to investigate the matter of these stray load losses advantage was taken of a small laboratory unit in a rather novel way. The unit used consists of a d-c. motor driving two identical 15-kw., three-phase, 110-220-volt generators mounted on the same shaft, one of which can have its stator shifted at will with respect to the other. By paralleling the two generators while driven by the motor and then shifting the stator of one of them, an electrical phase shift is introduced which forces the flow of power from one generator to the other. This power is returned to the first machine through the common shaft and hence the d-c. motor is only called upon to furnish the losses in the set.

Measurements of friction, windage, core loss, I^2R and stray

load losses were made by d-c. input in the customary Institute manner. The a-c. machines were then loaded into each other and the total d-c. input measured for various amounts of interchanged load. Fig. 1 shows how very closely the measured losses under actual loading correspond with the sum of the losses determined in the manner prescribed by the Institute rules.

Tests of this kind on a small, rather specially designed machine may at first sight appear to be incomparable with results to be expected on large commercial units, and yet the subdivision of conductors introduced on large, modern machines should accomplish somewhere near the same degree of eddy current isolation as exists in the laboratory machine.

Name of plant	Kva. of generator	Date of mfr.	Voltage	Rated power factor	R.p.m.	Type of generator	Friction and windage	Core loss	Stray and I^2R	I^2R	Stray
Drum No. 3	15,000	1916	6,600	0.80	360	Horizontal shaft	202.0	130.9	160.5		
Drum No. 4	15,000	1928	6,600	0.80	257	" "	107.7	89.5	120.0		
Pit No. 3	27,000	1924	11,000	0.90	225	Vertical	304.2	187.4	163.7	99.7	64
Pit No. 1	35,000	1921	11,000		257	"	200	302	220	126	94
Melones	13,500	1927	6,600	0.90	277	"	60*	80	120.5	78.5*	42*
Stanislaus	8,500	1907	4,000	1.00	400	Horizontal	80	75.3	94.3		
Electra	4,000	1905	2,400	1.00	400	"	82	68	32	16.8	15.2

*Factory value

Power Transmission and Distribution From the Mokelumne River Development of the Pacific Gas and Electric Company

BY E. M. WRIGHT[1]
Member, A. I. E. E.

and

B. D. DEXTER[1]
Member, A. I. E. E.

Synopsis.—*The additional power generated on the Mokelumne River has a peak capacity in excess of 150,000 kw. It is transmitted over a double-circuit 220-kv. transmission line approximately 109 miles to Newark substation where it is fed into the existing 110-kv. and 60-kv. networks of the Pacific Gas and Electric Company.*

Newark substation has rapidly grown into the most important substation on the system and numerous alterations and additions have been made from time to time to provide increased capacity. The addition of 150,000 kw. of peak capacity into this station has necessitated a major rebuilding and it has now become a twin station, divided into two major parts for the purpose of reducing oil circuit breaker interrupting duties and lessening the concentration of power on a single bus.

In addition to the two 220-kv. Mokelumne lines, there are sixteen 110-kv. and three 60-kv. transmission circuits radiating from Newark substation. With the final addition of the third transformer bank for incoming Mokelumne power there will be 249,000 kva. of transformer capacity and 75,000 kva. of synchronous condenser capacity connected to the bus.

The Mokelumne River Development consists of two major storage reservoirs and four power houses. From this development it is necessary to carry the power over 100 miles to a central distribution point. The existing lines from this territory consist of one 60-kv. wood pole line. It is, therefore, necessary to consider transmission lines and substation facilities which would take care of the entire development. The storage reservoirs and power houses are described in a companion paper, "Hydroelectric Development on the Mokelumne River," by E. A. Crellin, see page 28.

THE transmission line will extend in two circuits from Tiger Creek power house, the major plant, in a southeasterly direction for approximately 109 mi. (175 km.) to Newark, the position chosen for the substation, at the south end of San Francisco Bay.

En route, the line crosses the ultimate 220-kv. twin-circuit tower line from the Feather River hydroelectric plants, to the San Joaquin Light and Power Corporation's proposed steam plant near Fresno. Both of the Mokelumne River circuits are tapped through a switching station at this point of crossing, and feed south on one circuit on the No. 2 position of this tower line, about 100 mi. (161 km.) to the San Joaquin Light and Power Corporation's substation near Fresno. The Mokelumne lines also generally parallel for the last half of their lengths, two separate 110-kv. twin-circuit tower lines, one from the Spaulding-Drum hydroelectric development in the northwest and the other from the Stanislaus hydroelectric development in the eastern part of the company's territory.

An extended study, with due regard to the above conditions as well as for future ties to the company's existing system, showed that a voltage of 220 kv. would deliver the power with less cost per kilowatt-hour than would 110 kv. The receiving voltage at Newark was set at 200 kv. to permit future interconnection with Vaca-Dixon substation and the lines from the Pit River development. Sending voltage was set at 215 kv. so that charging current would be supplied from the receiving end and generators would operate at unity or lagging power factor and thereby require high excitation essential for good stability.

1. Pacific Gas & Electric Co., San Francisco, Calif.

Presented at the Pacific Coast Convention of the A. I. E. E., Lake Tahoe, California, August 25-28, 1931.

110-Kv. Line

In addition to the 220 kv., there is a single circuit line from Salt Springs to Tiger Creek power house. On account of the smaller amount of power available at the Salt Springs power house, 110 kv. was found to be best suited to this circuit.

The 110-kv. line is approximately 17 mi. (27 km.) long and generally parallels the Mokelumne River at an elevation of 3,800 ft. (1,158 m.) at Salt Springs, and 2,400 ft. (732 m.) at Tiger Creek, reaching 5,000 ft. (1,524 m.) about half-way between. Due to the snowfall in this territory, the circuit is in flat configuration, 14½ ft. (4.42 m.) between conductors, on snow-type towers with concrete foundations. (Fig. 2.) The conductor is 4/0, 7-strand medium hard-drawn bare copper except in some long spans where 4/0 "Hitenso" copper is used for the additional strength required. All splices are the drawn-joint type and were put on in the field with a portable draw-bench built for the purpose. Standard strength suspension type insulators in strings of eight 10-in. (25.4 cm.) units were used at all suspension points with nine units at most dead-ends. High strength insulators in strings of nine 11-in. (28 cm.) units were used at several dead-end points where the strain was excessive, such as at high points in the line. The normal span is 600 ft. (183 m.) but a number of spans are between 1,500 ft. (457 m.) and 2,100 ft. (640 m.). Transpositions are the rolling type without dead-end, and are completed in three normal spans by carrying one outside wire over the top of the other two on extensions attached to the top of two standard towers. A minimum angle is maintained at all insulator supports by offsetting the transposition towers. (Fig. 3.)

220-Kv. Towers

The 220-kv. transmission line starts from Tiger

Creek power house at an elevation of 2,400 ft. (731 m.) and ends at Newark at an elevation of 7 ft. (1.1 m.) above sea level. It consists of two general types of towers and two types of conductors, and is divided into three types of loading and also three zones of insulation. Neither the types of towers, conductors, loading or insulation sections coincide with each other exactly so that an explanation of each must be given separately.

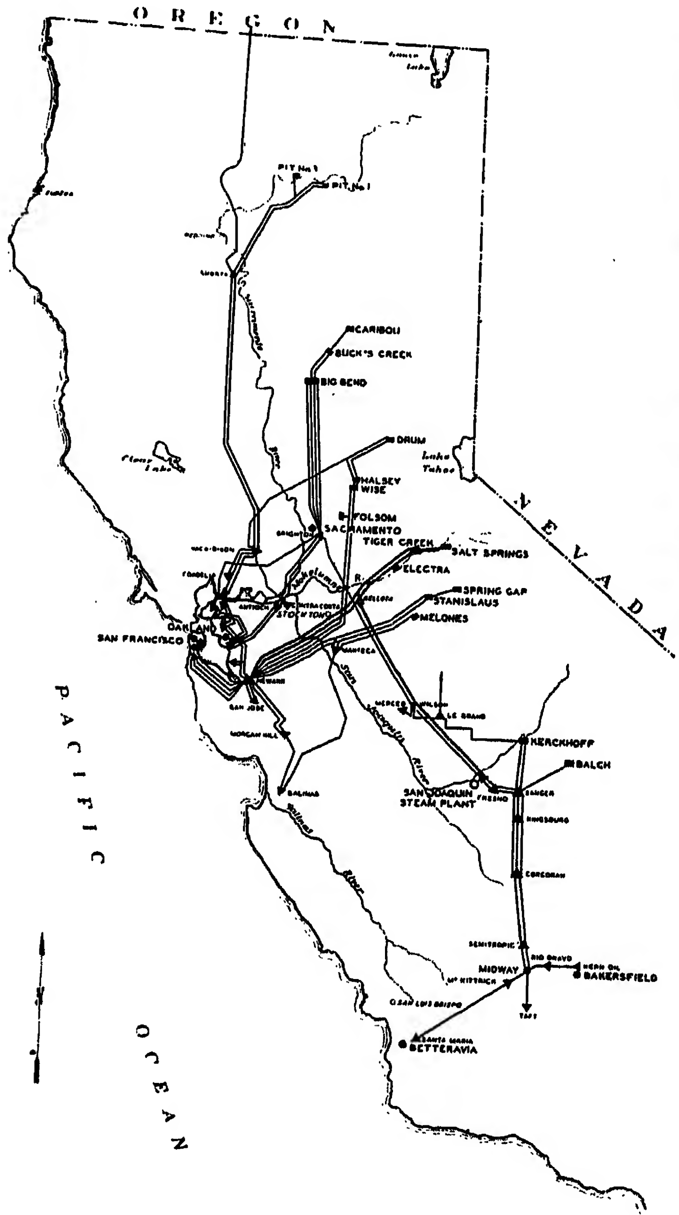

FIG. 1—110, 165 AND 220-KV. TRANSMISSION SYSTEM

In the heavy loading area, which provides for ½-in. (12.7 mm.) ice, and 6 lb. per sq. ft. (29.3 kg. per sq. m.) wind at 0 deg. fahr. (– 17.8 deg. cent.) and covers 16 mi. (25.7 km.) of line, there are two lines of single-circuit snow-type towers with concrete foundations. The circuit is in flat configuration with a horizontal separation between adjacent conductors of 20 ft. (6.09 m.) (Fig. 4).

The medium loading area provides for ¼ in. (6.35 mm.) of ice and 6 lb. per sq. ft. (29.3 kg. per sq. m.) wind at 0 deg. fahr. (– 17.8 deg. cent.) and covers a line distance of 11 mi. (17.7 km.). In this section of line there are twin-circuit steel towers on concrete foundations. These towers permit a semi-vertical configuration for both circuits with the center conductor offset 5 ft. (1.52 m.) outward giving 15 ft. (4.57 m.) separation

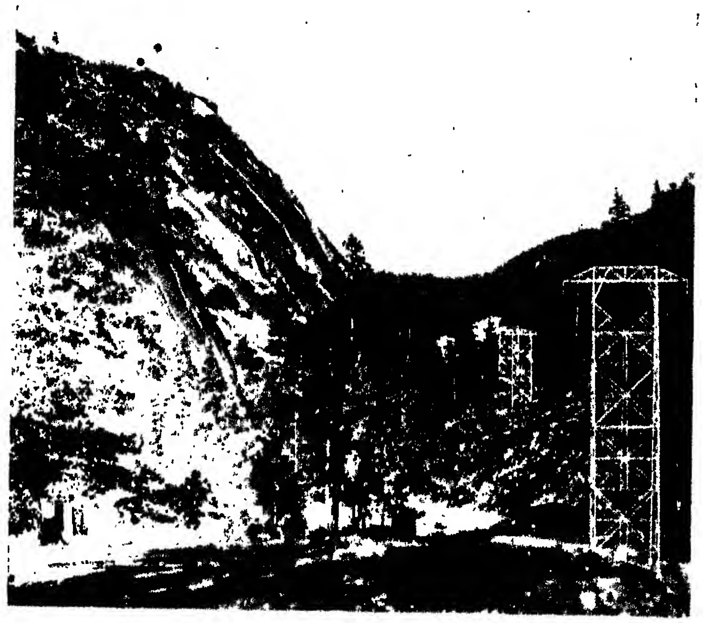

FIG. 2—110-KV. TOWER LINE NEAR SALT SPRINGS POWER HOUSE

between the conductors vertically, 28 ft. (8.53 m.) horizontal separation between the top wires and bottom wires of the different circuits and 38 ft. (11.58 m.) horizontal separation between the middle wires of the different circuits. (Fig. 5.)

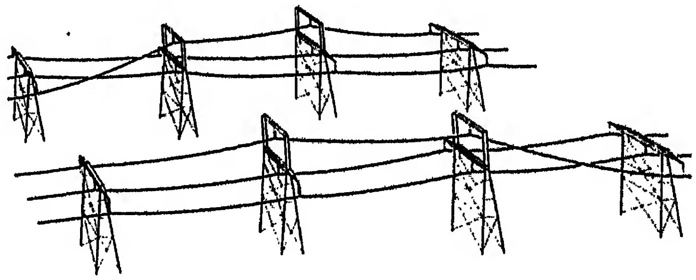

FIG. 3—TYPES OF TRANSPOSITION STRUCTURES AND METHOD OF TRANSPOSING WIRES IN SNOW TERRITORY ON 110-KV. AND 220-KV. LINES

The structures in the light loading area permit a loading of an 8 lb. per sq. ft. (39.1 kg. per sq. m.) wind at 25 deg. fahr. (– 3.9 deg. cent.). This area covers the remaining distance to Newark 82 mi. (132 km.) but is divided into two sections as far as towers are concerned. The first section, 53 mi. (85 km.) covers the entire valley from Valley Springs to Tracy and consists of towers the same as in the previous section except that

the center conductors are not offset. (Fig. 6.) The remaining section 29 mi. (46.6 km.) is considered fog area, and contains structures having the same steel, below the crossarm, as the previous sections. The crossarms are longer and farther apart and provide a

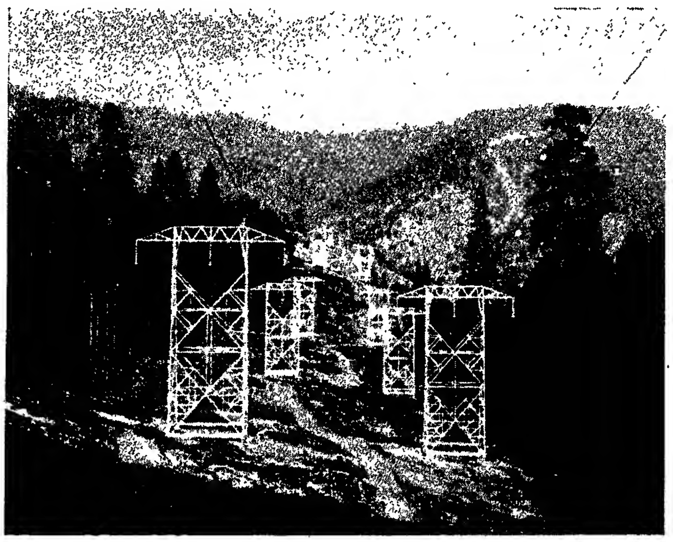

Fig. 4—220-Kv. Tower Line Near Tiger Creek Power House

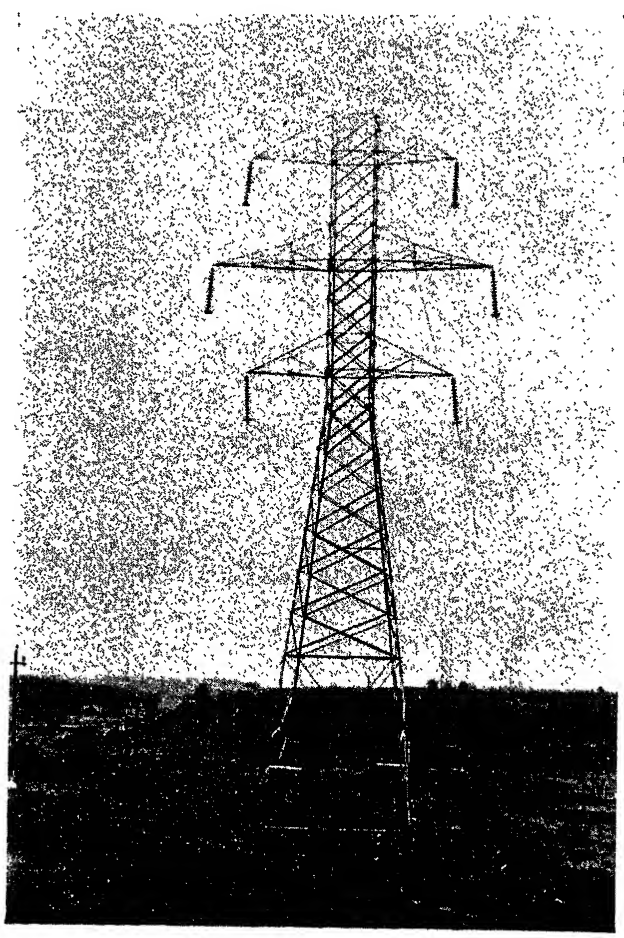

Fig. 5—220-Kv. Tower Line in Medium Loading Area, Showing Transposition Scheme

vertical separation between conductors of 18 ft. (5.48 m.) and a horizontal separation between circuits of 33 ft. (10.06 m.). These larger spacings are used to permit increased insulation. (Fig. 7.)

The normal span on the snow-type towers is 600 ft. (183 m.) and on the twin-circuit towers 800 ft. (244 m.) but there are many spans from 1,000 ft. (305 m.) to 1,800 ft. (549 m.) in length. Towers of the same type but of increased strength are used where necessity requires, but no dead-ends or semi-strains are used unless required for angles, up-strains or crossings.

Transpositions on the snow-type towers are made the same as in the 110-kv. section but in the twin-circuit section they are made by separating the circuits and

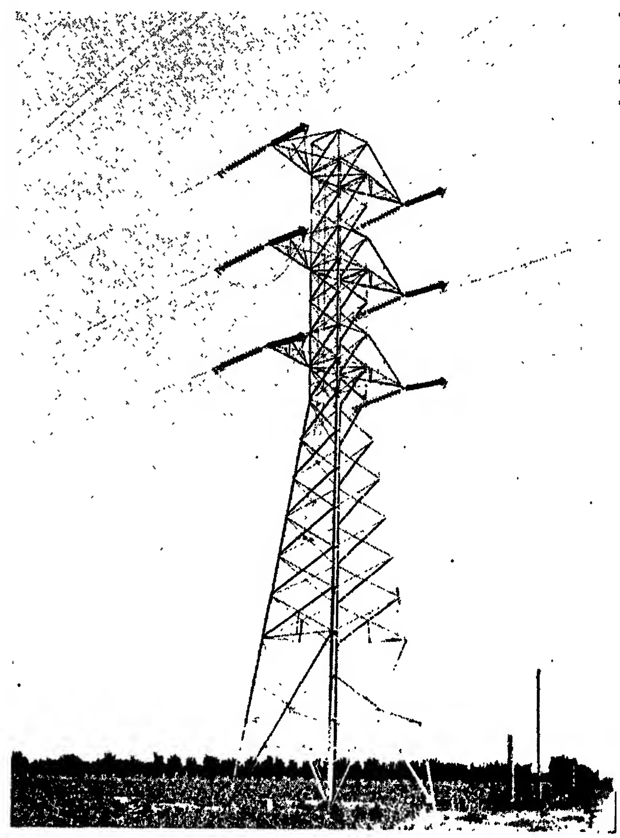

Fig. 6—Dead-End Tower in Light Loading Area

adding an extra tower at the center of the transposition. Normal spans are sufficient and the rolling type of transpositions, without dead-end, is used. (See Figs. 5 and 8.)

Conductors

Preceding the choice of conductors, extensive tests were made at Ryan Laboratory, Stanford University, on a three-phase, 220-kv. line under various spacings, positions and weather conditions, to determine corona losses for cables of various diameter. As a result of these tests two different types of cable were chosen. (Trans. A. I. E. E., March 1931, Vol. 50, p. 36.)

Between Tiger Creek and Valley Springs, 27 mi.

(43.5 km.), the heavy and medium loading area, where higher strength was required due to snow and sleet, aluminum cable steel reinforced was chosen. This cable has 518,000 cir. mils (334.2 cir. mm.) of aluminum and an outside diameter of 1 in. (2.54 cm.). The stranded steel core is approximately ⅝ in. (15.9 mm.) in diameter. Standard, Aluminum Company of America, compression joints were pressed on in the field for all splices.

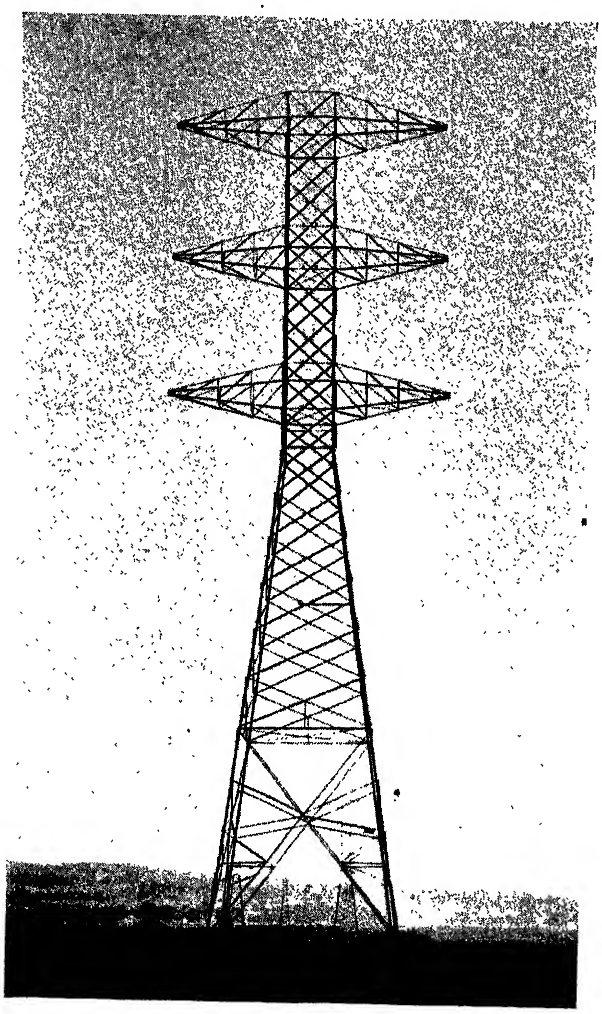

Fig. 7—220-Kv. Tower in Fog Section

The stringing tension at 60 deg. fahr. (15 deg. cent.) in the heavy loading area is 3,200 lb. (1,460 kg.) and in the medium loading area it is 4,200 lb. (1,920 kg.). Under maximum conditions the tension is approximately 7,000 lb. (3,200 kg.) in both cases.

Between Valley Springs and Newark Substation, 82 mi. (132 km.) where conductivity as well as low corona loss was of primary importance, hollow-core copper conductor was chosen. This conductor is 500,000 cir. mils, 1 in. (2.54 cm.) outside diameter and has two layers of 0.097 in. (2.46 mm.) diameter wires laid over a twisted copper I beam. The splices are screw joints and consist of threaded lugs drawn on the ends of the conductor in the factory and connected in the field by means of a sleeve nut. The entire joint is similar to a pipe union and, on account of right and left hand threads, is completed in the field without the necessity of twisting the conductor on either side. Where necessary to make an emergency splice in the field, either during construction or in case of failure during operation, a single piece sleeve is provided, to be drawn on with a portable draw-bench kept on hand for that purpose (Fig. 9). This drawing on process is done in the field the same as in the factory and differs only in respect to the portability of the machine used. The stringing tension at 60 deg. fahr. (15 deg. cent.) is 6,100 lb. (2,800 kg.) and for maximum conditions is about 7,200 lb. (3,300 kg.)

Hardware

The suspension clamps and dead-end clamps were made up specially and correspond very closely to the standard *J* and *U* bolt clamps used on many of the transmission lines. Particular attention was paid to the fitting of the clamp around the conductor so that the conductor would be in contact for not less than 80 per cent of its circumference. The standard suspension clamps are of the J-bolt type and are used at all suspension points except special railroad and important crossings. At these points the same type of clamp is used with U-bolt so that in case of failure the wire will not slip. U-bolt clamps were used at all dead-end points, thus eliminating any cutting of the wire.

Insulation

The insulation is divided into three sections: standard, light fog, and heavy fog. All insulators are ball socket type. In the first section from Tiger Creek to a point near Tracy, a distance of 79 mi. (127 km.) there are 13 standard strength 10-in. (25.4 cm.) suspension type insulator units with 5.5-in. (14 cm.) spacing in the suspension strings and 13 high-strength 11-in. (28 cm.) units with 7-in. (17.78 cm.) spacing in the dead-end strings, on both circuits.

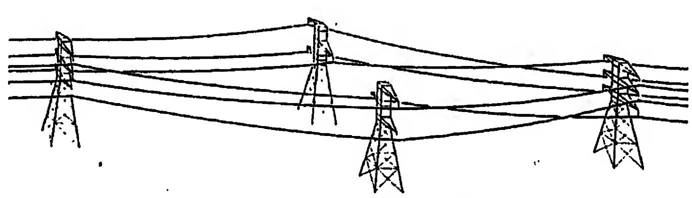

Fig. 8—Types of Transposition Structures and Method of Transposing Wires on 220-Kv. Twin Circuit Towers

The second section, in the light fog area from Tracy to Livermore, 11 mi. (17.7 km.), has 17 standard units as above in the suspension strings on the No. 2 circuit and 17 high-strength units as above in all dead-end strings on both circuits. The No. 1 circuit for the first half of the distance has 12 units of fog type insulators 10 in. in diameter with 6¼-in. (15.87 cm.) spacing and having a 3¼-in. (8.25 cm.) shell droop. This insulator is smooth

outside and has one petticoat on the inside. The last half of this light fog section has 11 units of fog type insulators 10 in. (25.4 cm.) in diameter and 7½-in. (19 cm.) spacing with three petticoats on the outside and smooth on the inside.

The heavy fog section from Livermore to Newark, a distance of 18 mi. (29 km.) has 20 standard units in

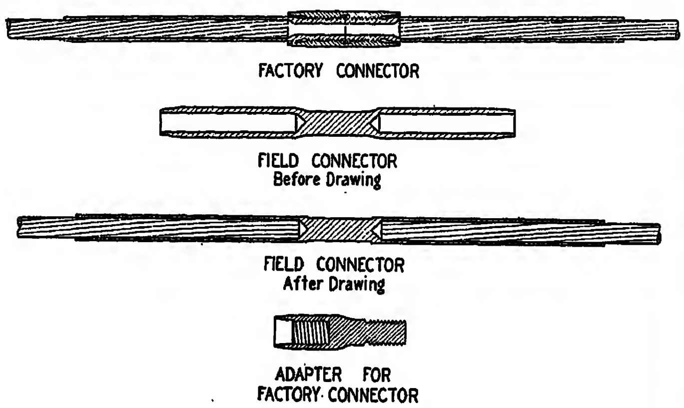

FIG. 9—TYPES OF CONNECTORS USED ON HOLLOW-CORE CONDUCTOR

suspension on the No. 2 circuit and 20 high-strength units in dead-end on both circuits. The No. 1 circuit for the first half of this distance has 13 of the 7½-in. (19 cm.) spaced fog units in suspension and for the last half of the distance has 14 of the 6¼-in. (15.87 cm.) spaced fog units in suspension.

to the relative values of the standard and fog type units under operating conditions.

A corona shield is installed on the line end of all insulator strings on the 220 kv. This shield is a round sheet of pressed steel curved down at the edge to protect the line hardware and connections from excessive corona losses.

FIG. 10—SECTION OF 220-KV. LINE NEAR TIGER CREEK POWER HOUSE

BELLOTA-SAN JOAQUIN TIE

Bellota substation is the switching station installed at the point where the Mokelumne line crosses the Feather River line. This point is approximately 42 mi. (67.5

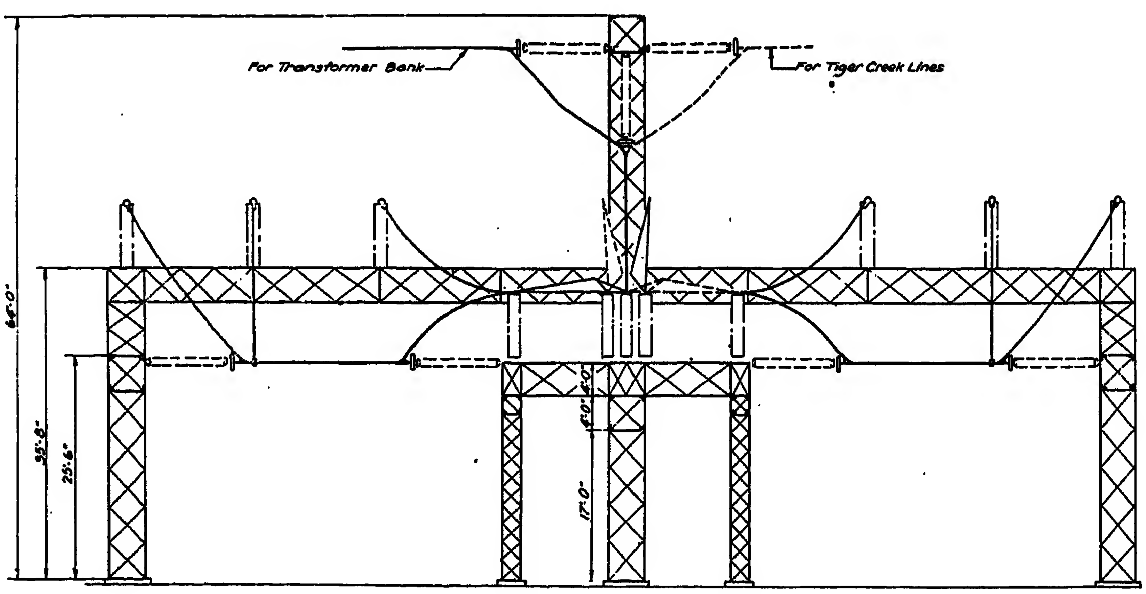

FIG. 11—SECTIONS OF 220-KV. BUS—NEWARK SUBSTATION

In all of the fog area, standard insulator units are used on one circuit and fog type units of two different designs are used on the other circuit, the length of strings of each type being in proportion to the recommended insulating value. From an experimental standpoint this should give some very useful information as

km.) from Tiger Creek. From Bellota substation one circuit extends on the existing tower line to the San Joaquin Light and Power Corporation substation near Fresno, approximately 100 mi. (161 km.). The conductor is bellow-core copper the same as on the Mokelumne circuits. The insulation is 14 standard units in suspen-

sion and 14 high-strength units in dead-end of the same types and spacing as on the Mokelumne circuits. All of the switching of the Bellota substation will be handled by remote control from Stockton, a distance of about 20 mi. (32.2 km.).

Newark Substation

Newark, the terminal station of the 220-kv. transmission line just described, has long been the distributing point of power from the Mokelumne River.

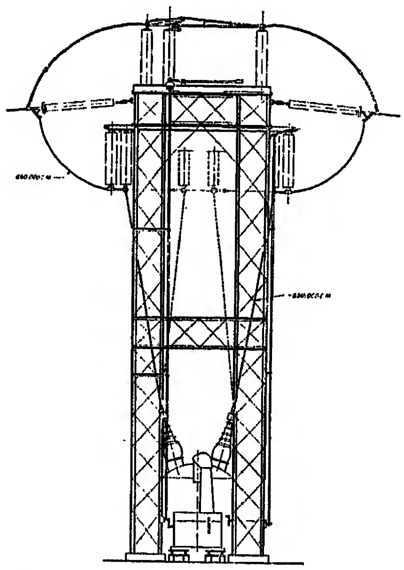

Fig. 12—220-Kv. Oil Circuit Breaker and Disconnecting Switch Structure—Newark Substation

It has been pointed out in the companion paper on the Mokelumne River Development* that the first delivery of power from the Mokelumne River was made in the year 1902 and that it was transmitted at 60 kv. The most distant delivery point was Martin Station in San Francisco, but among the more important intermediate switching stations was that located at Mission San Jose, some 15 mi. (24.14 km.) north of the City of San Jose. Some of the original equipment installed at this substation was in use up to 1919, when it was found that more modern facilities must be provided, and as space requirements could not be satisfied at this location it was decided to abandon Mission San Jose substation and build a new station about four miles further south and near the town of Newark.

The facilities at Newark substation in 1919 provided for the continued reception of Mokelumne River power at 60 kv. but as this source of supply was somewhat diminished due to the growth of load between Electra power house and the San Francisco Bay region it was necessary to deliver power to Newark substation at 100 kv. from the Spaulding-Drum hydroelectric development. In 1930 growth of load in the territory supplied from Newark substation required still larger amounts of power and delivery of same is now being made at 220 kv. from the Mokelumne River Development, thus marking the use of a still higher voltage and the handling of larger amounts of power at this important load center.

In order that an economical and yet flexible switching arrangement might be provided for handling the 220-kv. circuits it was decided to use a double bus with bus selector air switches and a single oil circuit breaker for each transmission line and transformer bank. With this arrangement a circuit can be connected to both buses or to either bus as switching requirements may dictate. This bus structure provides switching facilities for the operation of two transmission lines, three transformer banks, bus paralleling oil circuit breaker and carrier-current telephone coupling equipment.

As shown in Fig. 11, the buses and selector switches are placed well above ground and are supported on a galvanized steel structure. The general dimensions

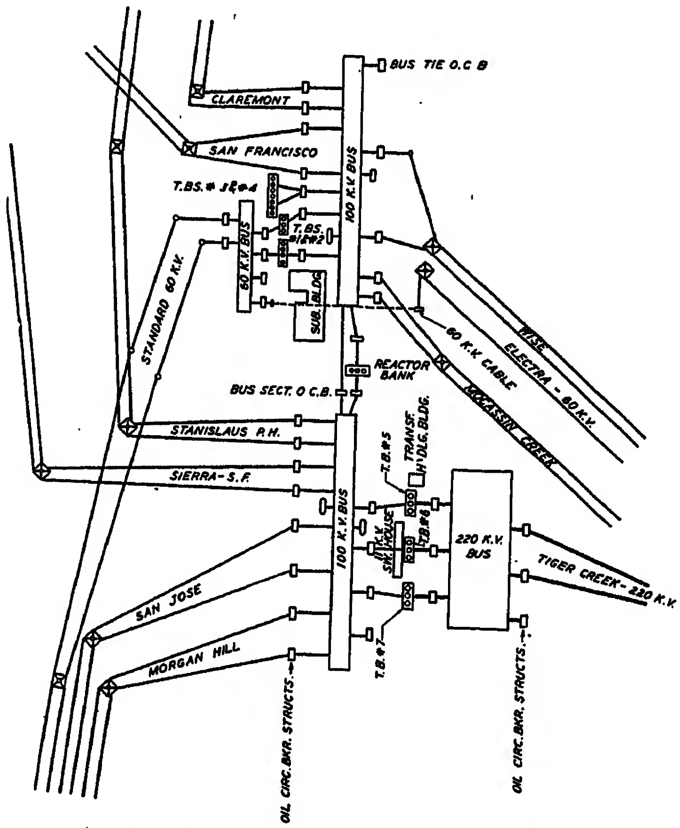

Fig. 13—General Arrangement of Newark Substation

of the structure are: length, 354 ft. (107.9 m.), width, 116 ft. (35.35 m.), height of center dead-end frame, 64 ft. (19.5 m.). The bus conductor consists of 650,000-cir. mils hard-drawn bare copper cable, concentric lay with 61 strands. The six conductors comprising the double bus are in tension and dead-ended on each end of the bus structure and supported on the cross frames with pillar type insulators at each bay.

The selector switches are rated at 400 amperes and are of the vertical break type. Each single-pole assembly consists of two single-pole air switches mounted

*Loc. cit.

on a common structural steel base, five insulator posts per pole being considered as most suitable. The three poles of each selector switch are actuated by a single manually-operated control handle located at the bottom of the supporting column adjacent to the selector switch assembly.

Connections from the bus structure to the oil circuit breakers are made at an elevation of 64 ft. (19.5 m.) and the center lines of the oil circuit breakers are located 98 ft. (29.87 m.) from the center of the bus structure. The two incoming 220-kv. lines and the bus tie breaker are on one side of the bus and the three transformer banks are on the opposite side.

The arrangement of a 220-kv. oil circuit breaker complete with by-pass and disconnecting switches and supporting structures is shown in Fig. 12. The arrangement is similar to that employed at other 220-kv. stations of the Pacific Gas and Electric Company, with exception of the use of a vertical break by-pass switch instead of the type P, or so-called "roller-skate" switch, which has been previously used. Inverted type P switches are used as disconnecting switches. On the switch towers which control the 220-kv. lines grounding switches are installed and mounted on the bases of the by-pass switches. Grounding is effected by closing the ground switch into a contact on the center post of the by-pass switch. Suitable interlocks are provided between the by-pass and disconnecting switches. All switches are actuated by means of rotary shafts and are hand operated. A galvanized structural steel tower is used to support the above switch and is 60 ft. (18.3 m.) high, 64 ft. (19.5 m.) long and 17 ft. (5.5 m.) wide. Within the tower enclosure a 6-break type, 600-ampere, 220-kv. oil circuit breaker is mounted with the poles of the breaker on 14 ft., 3 in. (4.3 m.) centers.

As mentioned above, provision has been made for three transformer banks and one spare transformer arranged for exchanging with any unit that must be taken out of service. These transformers are single-phase, auto-transformers, rated at 18,000 kva. and convert from 200,000 volts to 110,000 volts with a tertiary winding of 11,500 volts. Partial cooling is accomplished with radiators and additional cooling is obtained by means of hood type radiator air blast equipment. The units weigh approximately 200,000 lb. (90,720 kg.) each. The transformer output at 110 kv. is delivered to the 110-kv. bus and use is made of the 11-kv. winding for the operation of synchronous condensers. To facilitate the handling of transformers both for the initial installation and any subsequent maintenance work a permanent handling house has been constructed. This building is equipped with a traveling crane and all necessary tackle for untanking.

The 110-kv. bus is of the double-bus, single-breaker type and the switching arrangement is the same as that used on the 220-kv. bus. The buses and selector switches are mounted on a rigid steel framework with all live parts well isolated by elevation. The bus conductors consist of 2 in. (5.08 cm.) outside diameter, 14 gage (2.108 mm.) copper tubing and the bus and selector insulators are pillars made of two 20-in. (50.8 cm.) high, 4-part units per post. This bus is divided into two sections and provision is made for controlling 12 circuits in each section.

Due to the large concentration of power at Newark, particularly with the advent of power from the Mokelumne project, it was considered advisable to install current limiting reactors in one bus between the bus sections. Attention is called to the fact that this substation is essentially two stations, the dividing line being the reactor bank between the 110-kv. bus sections. One part is comprised of the older equipment consisting of several 110-kv. circuits, 60-kv. circuits, transformer banks and synchronous condensers, the second part consists of the new 220-kv. circuits, together with the associated 220/110-kv. transformers, 110-kv. circuits

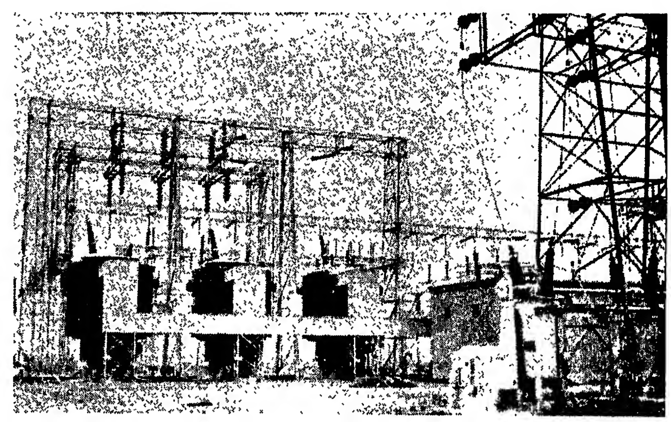

FIG. 14—REAR ELEVATION 220/110/11-KV. TRANSFORMER BANK NEWARK SUBSTATION

and synchronous condensers. The three current-limiting reactors mentioned above are rated as follows: 5,400-kva., single-phase, 60 cycles, outdoor-type, 110,000 volts, reactance 60 ohms, 300 amperes continuous capacity with an overload capacity of 1,060 amperes for 3 sec. Externally operated tap changers are provided. These are the largest oil-filled reactors ever built, the approximate weight of each is about 85,000 lb. (38,500 kg.).

Consistent with the dual station principle, it was necessary to make the switchboard in two sections, each section arranged to control its respective group of equipment. Due to the large number of circuits involved it was found necessary to use a benchboard and two vertical boards, one for the indicating instruments and the second for relays. In order to reduce the over-all length of the switchboard, two circuits per panel were found necessary, one circuit being above the other, this arrangement forcing the use of 100-in. (254 cm.) high

panels in place of the conventional 90-in. (228.6 cm.) panels. The entire switchboard is constructed of 1/8-in. (3.17 mm.) stretcher-leveled steel.

The synchronous condenser equipment for the new station consists of two machines each rated as follows: 25,000 kva., 720 r. p. m., 11,500 volts, three-phase, 60-cycle. These machines are of the totally enclosed ventilated type equipped with surface air coolers. Pedestal bearings are provided with passage for cooling water in the bearing shells. Fire extinguisher manifolds are installed at the ends of the stator frame around the air-gap. Water at 25 lb. per sq. in. (1.76 kg/sq. cm.) will be used for fire fighting. Each condenser is provided with a main and sub-exciter and one machine is built with a 1,500-hp. synchronous driving motor. This latter device is required for line and relay testing. This feature is particularly applicable to this station where three main transformer banks are to be used, for with this grouping a bank can be released for build-up tests without great impairment of capacity.

The switching equipment used in connection with the operation of the condensers is of the metal enclosed type using truck type oil circuit breakers and motor-operated disconnecting switches. This equipment is housed in a small building adjacent to the 220-kv. transformers and underground lead-covered cable connections are made between the switching equipment and the condensers.

In unifying the existing and new control equipment in a new switchboard room considerable planning was necessary in order to arrange conduits in such a way that the transfer of control circuits could be made from the old station to the new and service maintained at all times. This was facilitated to a large extent by the use of a control circuit terminal room located directly beneath the switchboard room. All switchboard wires and control circuits are brought to terminal blocks and all cut-over work and testing procedure was readily executed.

Carrier current telephone equipment has been installed which will provide for communication over the 220-kv. lines to Tiger Creek power house and also by means of the 110-kv. circuits to Oakland, where a wire line extension is made to the Load Dispatcher's office. The coupling condensers on the 110-kv. and 220-kv. buses are so connected that the dispatcher may communicate directly with Tiger Creek power house without assistance from the Newark operator.

As pointed out above, Newark substation as it is now constituted is the result of many additions. Other stations previously chosen as transmission line centers and designed with the idea of future expansion have each in turn failed to develop their expected importance due to the shifting of load centers or to changes in transmission voltage. This station, however, not originally considered as likely to be greatly expanded, has grown step by step into the largest and most important transmission center on the system and it is worthy of comment that in spite of the many additions and the changing importance of its position, the flexibility of the unit structures used has allowed it to develop into a rational arrangement. Except for the old switchboard just replaced, every structure, whether installed in 1919 or in 1931 is functioning in its logical location as part of a modern substation.

In view of the fact that it is impossible to make accurate predictions as to the location of future load growth and the routing of transmission circuits to supply this load, it becomes necessary to design and construct major transmission substations in such a manner that they can be readily extended in any direction without the necessity of moving existing equipment or giving the appearance of a patched up job. Satisfactory operation requires a simple and easily followed arrangement of equipment. Proper thought given to the design of the original installation will permit the achievement of these aims even though the station grows far in excess of any preconceived ideas as to its probable future importance.

The Mokelumne River Development

of the Pacific Gas and Electric Company

BY E. A. CRELLIN*

Fellow, A. I. E. E.

Synopsis.—Studies of topography and run-off have made possible a comprehensive development of the power resources on the Mokelumne River in California. Originally developed in 1902 to yield 100 million kw-hr. annually, additional storage and increased generating facilities will produce a ten-fold increase in annual output. Two major storage reservoirs and four power houses, one of which replaces the original plant completed in 1902, are included in the program.

The entire project is expected to be completed by the summer of 1935 at which time the total fall of more than 5,000 feet available in the Mokelumne River drainage area will have been put to the most economical usage.

EACH growing power system must from time to time add new generating capacity to care for increasing load demands. A new steam plant is added here, or a new hydro plant there, as will best meet the physical and economic requirements of the system. Usually these new plants feed into existing facilities which are reinforced to carry the additional burden. Not often does such an addition of generating equipment involve all of the features of a complete power system from the study of water storage and usage through generation and transmission to the step-down substation. It is this aspect of the Mokelumne River Development of the Pacific Gas and Electric Company which makes it of more than passing interest. This paper will treat of the hydroelectric features of the project while a companion paper will cover the transmission and substation design.

The Mokelumne River is one of the pioneer power streams of California. It has its source in Alpine County approximately twenty miles south of Lake Tahoe at an elevation of 9,700 ft. (2,950 m.) above sea level and flows in a general southwesterly direction for some 120 mi. (190 km.) where its waters join the San Joaquin River on their way to the Pacific Ocean through San Francisco Bay. The junction of the Mokelumne and San Joaquin Rivers is only a few feet above sea level and the lower 60 mi. (95 km.) of the river is quite flat lying at an elevation of less than 200 ft. (60 m.) above sea level.

The discovery of gold and its accompanying need for water for mining operations brought about the first developments on the Mokelumne River. In the fall of 1857 a company was formed which built canals and diversion works to deliver water to the miners. This company and its successors continued in the water business until the properties were acquired by the Standard Electric Company of California in the late nineties for the purpose of generating power for transmission to San Francisco, 110 miles (177 km.) away.

*Asst. Engineer, Div. of Hydroelec. and Trans. Engg., Pacific Gas and Electric Co., San Francisco, Calif.

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Electra power house and its associated 60-kv. transmission line were placed in service May 6th, 1902, one of the pioneer hydroelectric and high-voltage transmission projects of the world. The original installation of five 2,000-kw. units was increased by the addition of two 5,000-kw. generators in 1907 and the plant has been in continuous operation since it was first placed in service.

Water storage facilities on the upper reaches of the Mokelumne totaled approximately 25,000 acre-ft. (31,000,000 cu. m.) divided among several small reservoirs located at relatively high altitudes. This water, released as needed to augment the natural flow of the river, was diverted in the vicinity of the junction of Tiger Creek and the Mokelumne River into two canals each approximately 20 miles (32 km.) in length and with a combined capacity of some 200 cu. ft. per sec. (5.66 cu. m.) for delivery into the forebays above Electra power house. The annual output of power from the system was approximately 100 million kw-hr. The foregoing introductory remarks are intended to disclose the conditions existing at the time studies for the development of additional power on the Mokelumne River were begun.

That portion of the Mokelumne River which lies upstream from a point near its junction with Tiger Creek was relatively inaccessible and only occasionally visited by sportsmen who were obliged to carry their equipment on pack animals. As a result of this condition, actual water record data for the upper portion of the water shed of the river were not available. From 1906 to the present time, complete records of stream flow have been kept of readings taken at gaging stations located near the diversion into the conduit supplying water to Electra power house and beginning with the early spring of 1924 additional gaging stations were installed at strategic locations on the upper river and certain tributary streams.

The information obtained from these later stations was studied in connection with the long time record of the original stations and the run-off and storage possibilities analyzed for twenty-four consecutive seasons. Run-off characteristics for the upper and lower portions

of the river vary during the different months of the year. During the winter and early spring the precipitation on most of the upper basin is in the form of snow, while that on the lower portion of the development is rain. This means that two groups of run-off curves must be studied, those developed from run-off due to melting snow in the late spring and early summer months, and those derived from the autumn and winter rains. This study of precipitation and run-off has involved a vast amount of detail work and the results derived have withstood the test of actual observations during the past two seasons when it was possible to compare the stream flow readings of the upper river and its tributaries as sent in by the gage readers in the field with the predicted results as obtained from the formulas derived from the studies of the lower river records. This check on calculated data has inspired considerable confidence in the accuracy of the assumptions made as to the run-off from the several component parts of the drainage area.

From the water supply studies and accurate topographic maps it was possible to determine the most advantageous storage sites and to plan a comprehensive development for the most economical utilization of the water. A tabulation was prepared to show the probable use of storage water in maintaining a more or less uniformly regulated flow at the forebays of the various plants. Certain assumptions were made regarding the method of operation based on a workable plan which would permit the use of storage facilities and physical features to good advantage in meeting the demand for energy. Calculations of energy output were then made covering the conditions of average rainfall and of the maximum and minimum twelve consecutive months of rainfall for the twenty-four seasons for which records were available. It was found that the average year would yield approximately 913 million kw-hr., with 1,038 million for a year of full supply and 489 million kw-hr. for the dry year period.

Consideration was given to the necessity of having peak output sufficient to meet system load conditions at all times, it being assumed that on dry years peaks would be met by hydro power with steam power carrying the base load. Economic studies showed that the Mokelumne River development required back up steam capacity to the order of about 35 per cent of the peak, the hydro capacity representing 65 per cent of the peak. Likewise consideration was given to having a maximum release of stored water during the summer months, in order to give the most benefit to irrigation interests on the lower reaches of the river, which was consistent with maintaining peak demand throughout the late fall and winter. When the project is entirely completed it will involve a total storage of some 200,000 acre-ft. (247,000,000 cu. m.) of water and the generation of a billion kw-hr. annually, a ten-fold increase over the original Electra development.

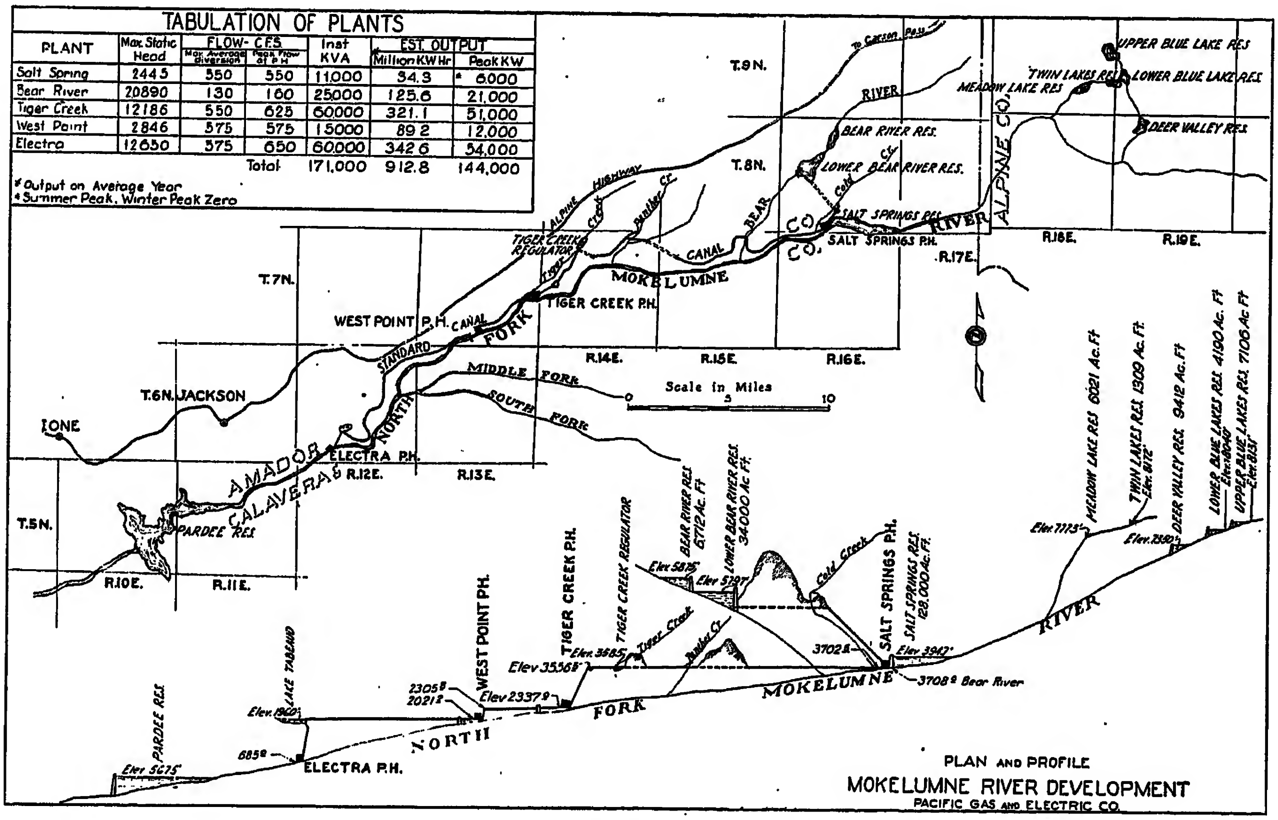


FIG. 1—PLAN AND PROFILE OF MOKELUMNE RIVER DEVELOPMENTS

Two major storage reservoirs, one known as Salt

Springs reservoir, and located on the Mokelumne River; the other known as Lower Bear River reservoir, and located on one of the principal tributaries of the upper Mokelumne are being created to impound the run-off waters from their respective drainage areas. The regulation of flow in the Mokelumne River made possible by these two storage reservoirs, together with the smaller reservoirs already in service is the principal factor contributing to the increased power output. The spillway elevation at Salt Springs dam is 3,947 ft. (1,203.04 m.) above sea level; that of the Bear River dam 5,816 ft. (1,772.72 m.). The center line elevation of the nozzles of the waterwheel units to be installed at Electra power house, which is the down stream end of the power development on the river, is 685 ft. (208.79 m.), thus giving a gross head of 3,262 ft. (994.25 m.) and 5,131 ft. (1,563.93 m.) respectively from the two main sources of storage.

The head available for the generation of power will be divided up into four sections and four power houses will be constructed. The several elements in the development will be briefly described, beginning with the upstream end of the system.

Salt Springs Dam

The Salt Springs dam site is located in the gorge of the Mokelumne River about a mile above the two natural landmarks, Calaveras Bald Rock on the south side of the gorge and Amador Bald Rock on the north side. These granite domes rise more than 3,000 ft. (900 m.) above the stream bed. The dam was started in 1929 and is the highest rock fill dam in the world.

Several considerations influenced the choice of a rock fill dam for this location. It is believed to be one of the safest kinds of dam that can be built and the rock fill type of dam has been very successful in California. The canyon is of solid granite, thus making available at the site ample material for its construction. Due to the inaccessible nature of the country in which the dam is located it was necessary to construct approximately 50 miles of roadway suitable for heavy trucking and to haul all materials 50 mi. (80 km.) by motor transport. The high cost of concrete materials at such a site made the estimated cost of a rock fill dam approximately two million dollars less than for a suitable concrete dam. Modern and large scale construction equipment was used on the job with electrically-operated shovels and storage battery operated locomotives hauling rock cars.

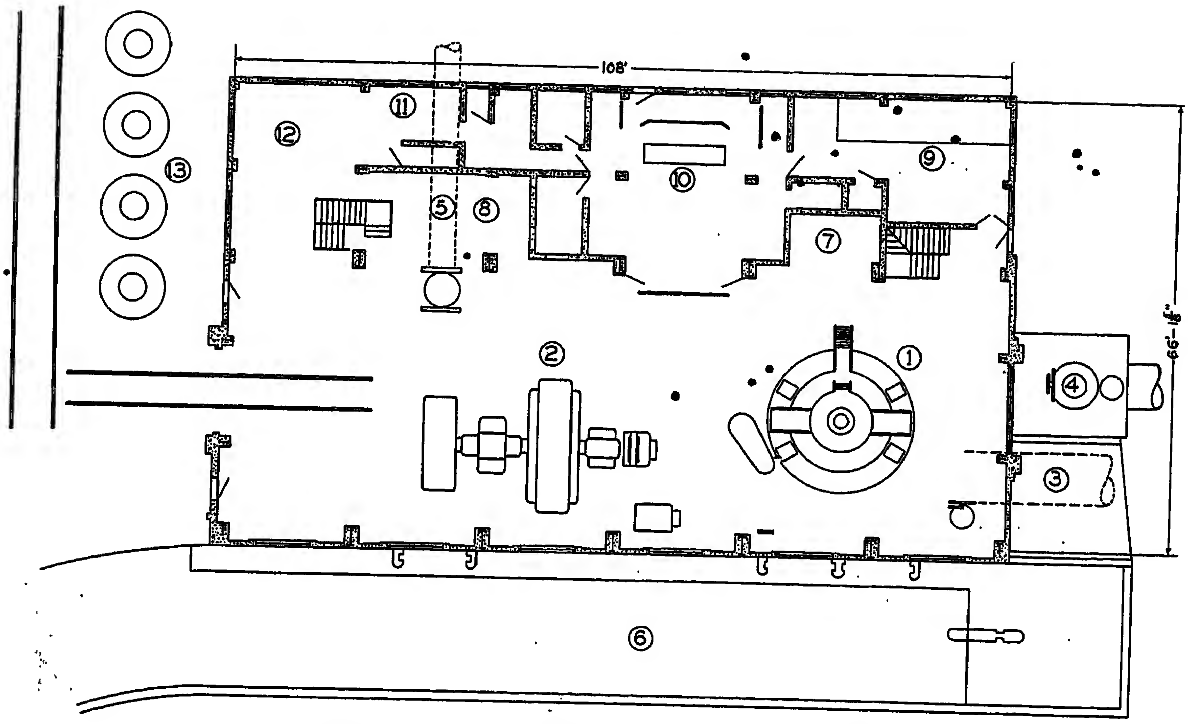
Rock for the dam was obtained from quarries at different levels near the north abutment of the dam and from the spillway excavation on the south bank. Quarrying methods followed, in general, usual practise and featured the breaking down of large volumes of rock with large charges of dynamite. Several "big shots" were made each of which required in excess of 50 tons (45,000 kg.) of powder and brought down approximately 200,000 cu. yd. (150,000 cu. m.) of granite.

The dam rises 328 ft. (100 m.) in height above the stream bed with a crest length of 1,300 ft. (396 m.). It is 900 ft. (274 m.) through at the base and contains approximately 3,000,000 cu. yd. (2,300,000 cu. m.) of material, of which approximately 225,000 cu. yd. (172,000 cu. m.) are in the derrick placed rock section having a uniform thickness of 15 ft. (4.57 m.) over the entire area of the upstream face of the dam. This placed rock forms a foundation for the outer facing of reinforced concrete which covers the entire upstream slope, varying in thickness from 36 in. (91.44 cm.) at the bottom to 12 in. (30.48 cm.) at the top. Concrete was placed in continuously poured panels of heavily reinforced concrete 60 ft. (18.3 m.) square. These panels are completely separated with expansion or contraction joints which are provided with copper

Fig. 2—Upstream Face of Salt Springs Dam

water seals. The horizontal joints were poured concrete to concrete except for a coating of asphaltic material. The vertical joints were provided with a 1-in. (2.54 cm.) spacing which was filled with asphaltic compounds to permit lateral movement.

Due to the probable settlement of rock fill in a structure of this kind, the crest of the dam was crowned, the maximum crown being six to seven ft. (1.83 to 2.13 m.) above the theoretical crest line. In order to take care of the downstream settlement due to water pressure from the reservoir, the upstream face was designed and constructed with an upstream convexity in plan. For similar reasons and to prevent possible buckling of the concrete face, the face was concave to the water surface in vertical section. The reinforcing steel does not extend through the joints. These provisions were made in order to provide as flexible a facing as possible. The facing contains about 30,000 cu. yd. (23,000 cu. m.) of concrete and has an area of about 9.2 acres (37,200 sq. m.). It is anchored to con-



Main Floor Plan of Salt Springs Power House

1. Vertical shaft reaction-type generating unit
2. Horizontal shaft impulse-type generating unit
3. Penstock for No. 1
4. By-pass penstock
5. Penstock for No. 2
6. Tail-race conduit
7. Governor oil pump
8. Governor oil pump
9. 440-volt bus structure
10. Bench board
11. Air compressor
12. Machine shop
13. Single-phase transformers

crete cut-off walls extending vertically from 5 to 25 ft. (1.5 to 7.5 m.) into solid granite. Grout holes extend some 50 ft. (15 m.) below the bottom of the cut-off wall.

Salt Springs reservoir has a capacity of 130,000 acre-ft. (160,000,000 cu. m.) is 4 mi. (6.4 km.) long and has a maximum width of three-quarters of a mile (1.2 km.). The flooded area is 925 acres (375 ha.). A spillway with a crest length of 625 ft. (190 m.) is channeled in the south side of the gorge adjacent to the dam. It has a capacity of 48,000 cu. ft. per sec. (1,360 cu. m/sec.) or 300 cu. ft. per sec. per sq. mi. of drainage area (89 cu. m/sec. per sq. km.). The freeboard under this condition is 8 ft. (2.44 m.).

The outlet works are at the north end of the dam and consist of two 10-ft. (3.05 m.) diameter steel pipes inserted into the downstream end of a 19-ft. (5.79 m.) diameter concrete-lined tunnel built originally as a diversion tunnel to facilitate construction of the dam. Each pipe is provided with a 10-ft. 9-in. (3.28 m.) diameter hydraulic-operated butterfly valve and is then extended on into the river channel where it ends in a 78-in. (1.98 m.) diameter butterfly valve designed for free discharge. These valves are provided to permit unwatering the reservoir at the rate of approximately 10,000 acre-ft. (12,300,000 cu. m.) per day in case of emergency, and are designed for a maximum head of 275 ft. (83.8 m.) making them the highest head free discharge butterfly valves yet installed.

A branch from one of these pipes forms the 8-ft. (2.438 m.) diameter penstock supplying water to the generating unit installed in Salt Springs power house located a few hundred feet downstream from the dam. A branch from the other pipe ends in a 54-in. (1.37 m.) needle valve in which is incorporated an energy absorber of the "through baffle" type which discharges into the power house tailrace. This bypass line is necessary in order to supply water into the Tiger Creek conduit, which heads in the tailrace, when the Salt Springs unit is shut down or when it is operating under reduced head.

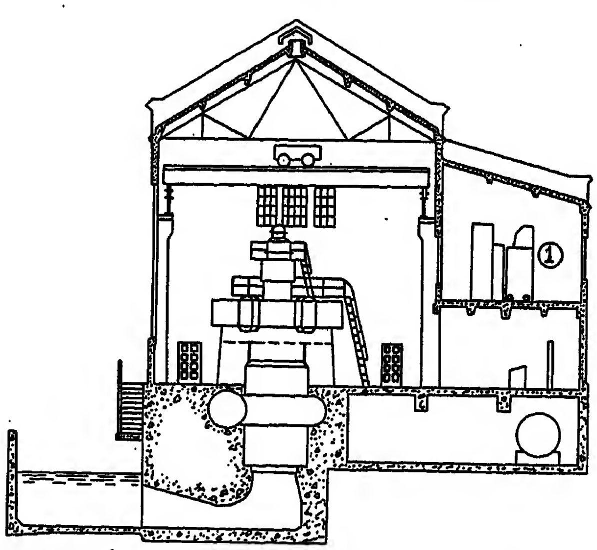
Bear River Water Supply

Bear River is one of the principal tributaries of the Mokelumne River. The drainage basin is high in elevation and the descent of the stream is rapid, the fall in the last 6 mi. (9.66 km.) above the junction with the Mokelumne being more than 2,500 ft. (762 m.). It is planned to construct a dam about 200 ft. (61 m.) in height in Bear River some 2.5 mi. (4 km.) below the existing dam which forms Upper Bear River reservoir. The new reservoir will have a capacity of 34,000 acre-ft. (42,000,000 cu. m.). A tunnel approximately 2.5 mi. (4 km.) in length will terminate in a penstock which leads to Salt Springs power house. The junction of the penstock and tunnel is formed in a surge chamber which will be excavated in the rock. The elevation of the top

of this surge chamber is above high water in Lower Bear River reservoir. Water from Cold Creek, a stream adjacent to and similar in character to Bear River but lacking storage sites, will be diverted into this surge chamber. By means of this arrangement the area above the diversion point on Cold Creek is made tributary to the reservoir on Bear River. No storage is provided on Cold Creek. Water diverted from Cold Creek is partly used through the power house and partly backed up through the pressure tunnel for storage in Bear River reservoir. Any spill from these sources may be stored in Salt Springs reservoir. The arrangement is ideal from the standpoint of ease in using the run-off from the different sources and insures complete conservation of all water resources to maximum usage.

Salt Springs Power House

Salt Springs power house will be a rather unique plant in that its two generating units will be radically different in design. Two sources of water are available to this plant, one being the water released from storage in Salt Springs dam under a static head of 244.5 ft. (74.52 m.); the other the water released from storage in Lower Bear River reservoir, which will be under a static head of 2,089 ft. (636.73 m.). In the first case the head and water quantities are such as to require the installation of a Francis type turbine, while the latter can only be utilized through an impulse wheel. Many problems in plant design were occasioned by the



Section of Salt Springs Power House

1. 11-kv. oil circuit breakers

different characteristics of these two prime movers. In keeping with the policy of the company, it was desired to secure a plant arrangement which would afford the greatest operating convenience in order to keep the personnel for plant operation at the minimum possible number of men. In general a vertical turbine with its draft tube setting requires a power house floor level considerably higher above tail water elevation than is desirable with an impulse wheel installation, and in order to maintain the power house floor on a single level, it was necessary to study the design and setting of the turbine with a view to keeping the power house floor as low as possible. The cooperation of the turbine builder was sought in the final designs and the unit was so constructed that it was possible to arrange its setting at an elevation which would also accommodate the impulse wheel. The high head unit will be installed at a future date following the completion of the dam and tunnel on Bear River but it was necessary to make considerable progress in the preliminary design of the impulse wheel unit in order to determine with some degree of accuracy what its probable dimensions would be. This also required cooperation with the waterwheel builders and preliminary designs were all based on the desire to secure a plant which would make for convenience in operation.

Fig. 3—Salt Springs Power House and Downstream Face of Salt Springs Dam

The Francis type turbine for utilizing the water released from Salt Springs dam is a vertical shaft unit designed to pass 550 cu. ft. per sec. (15.7 cu. m/s.) at heads as low as 175 ft. (53.34 m.) in order to accommodate the lowered level of water behind the dam as storage is withdrawn. In effect, this requires a turbine which must be operated at part gate under maximum head conditions with gate openings increasing as the head falls in order to maintain full load on the generator. At heads below 175 ft., it will be necessary to bypass water around the turbine into the tailrace in order to maintain the conduit flow at its full capacity. The turbine is rated at 13,500 hp., 300 r. p. m. It drives a vertical shaft waterwheel generator rated at 11,000 kva., 11,000 volts, 60 cycle, 85 per cent power factor. The generator is mounted on a concrete pedestal above the turbine and is totally enclosed with surface air coolers arranged at four points around the circumference of the generator. Contrasted to this will be

the horizontal shaft unit installed to utilize the water from Bear River reservoir. This waterwheel will be a single overhung impulse unit capable of developing approximately 35,000 hp. at 300 r. p. m. The probable generator rating will be 30,000 kva., 11,000 volts, 60 cycles, 85 per cent power factor.

Both units will disharge into the same tailrace which forms the intake for the conduit supplying water to Tiger Creek power house. The discharge from a turbine is relatively still and offers no problems in connection with feeding into such a conduit. On the other hand, the discharge from an impulse wheel upon the rejection of load must be carefully handled if it is to be confined into the narrow limits of such a tailrace and designs have accordingly been laid out for the incorporation in the power house foundations of an energy absorbing device of the "through baffle" type. In this device the jet of water which has been deflected from the waterwheel runner by means of the governor actuated sleeve surrounding the nozzle tip impinges on a splitter which turns the water back on itself, thus destroying the energy of the jet and permitting it to flow outward freely into the tailrace. Such devices have been used in previous high-head installations on the Pacific Coast and have proven thoroughly reliable and successful.

The capacity of the Tiger Creek conduit is 550 cu. ft. per sec. (15.57 cu. m/s.), and it is desired to maintain this flow practically constant in order to supply water to Tiger Creek power house down stream. At full load the turbine unit will pass 550 cu. ft. per sec. and deliver power up to the 11,000-kva. rating of the generator. On the other hand, the impulse unit will pass approximately 180 cu. ft. per sec. (5.1 cu. m/s.) and deliver power up to the full rating of its generator which will be 30,000 kva. or slightly above. Thus it is seen that by properly adjusting the load between the two generating units in the plant it will be possible to maintain a constant flow in the conduit at plant outputs which will vary between the limits of 11,000 kva. or less, depending upon the height of water behind Salt Springs dam and 37,500 kva., as may best suit the load requirements of the system.

The low-tension switching arrangement in the plant is simple. Each generator is connected to a main bus through a single truck type oil circuit breaker. Two additional truck type breakers feed power from the main bus into the station power transformer bank. The two breakers supplying the station transformers are arranged so as to be interchangeable with the main generator breakers. While this required extra large breakers for the service demands the added cost was greatly offset by the simplicity of the arrangement and the possibility of taking any oil circuit breaker out of service for inspection or repairs without any loss in plant output.

From the main 11-kv. bus, leads are run direct to the step-up transformer bank consisting of three 12,000-kva., 11-kv. to 110-kv. water-cooled transformers. A spare transformer is provided and arranged to permit of its substitution for any unit in the bank by means of air-break selector switches. The output from the step-up transformer bank is fed through a 115-kv. oil circuit breaker into a single-circuit steel tower transmission line for delivery to the main 220-kv. step-up transformer banks at Tiger Creek power house.

Tiger Creek Conduit

Water discharged from Salt Springs power house is diverted from the tailrace into Tiger Creek conduit which has a capacity of 550 cu. ft. per sec. (15.57 cu. m/sec.). This conduit is 17.3 mi. (27.84 km.) in length and terminates in a regulating reservoir on Tiger

Fig. 4—A Section of the Salt Springs-Tiger Creek Conduit

Creek. From the regulator a conduit of 625 cu. ft. per sec. (17.7 cu. m/sec.) capacity extends 2.6 mi. (4.18 km.) to a small forebay at the head of the penstock to Tiger Creek power house. The conduit is composed chiefly of reinforced concrete flume with a water section of 84 sq. ft. (7.8 sq. m.) and a water depth of 6 ft. (1.83 m.). The grade of the portion from the intake to the regulator is 0.8 ft. (24.38 cm.) per 1,000 ft. (304.8 m.) and the grade of the portion between the regulator and the forebay 1.0 ft. (30.48 cm.) per 1,000 ft. (304.8 m.). Part of the flume is elevated but in the main it is of the bench type. In addition to the flume there are two steel siphons, 93 in. (2.36 m.) in diameter totaling in length 0.23 mi. (370 m.), and 2.5 mi. (4 km.) of unlined tunnel with a section 10 ft.

(3.05 m.) wide by 11.3 ft. (3.44 m.) high on a grade of 3.5 ft. (1.07 m.) per 1,000 ft. (304.8 m.).

The topography of the country in the vicinity of the site chosen for the construction of Tiger Creek power house did not offer any suitable location for a forebay which would have sufficient capacity for the regulation of flow in the conduit and the carrying of short duration peaks and a compromise was made by the creation of a pond about 2.6 mi. (4.18 km.) up stream from the forebay site. This pond is known as the Tiger Creek regulator and is formed by a buttressed slab concrete dam approximately 100 ft. (30.48 m.) high on Tiger Creek. The upper 18 ft. (5.49 m.) of the reservoir thus formed provides about 175 acre-ft. (216,000 cu. m.) of capacity. This is sufficient to permit peaking the Tiger Creek plant for 20 hours each day when full diversion is being made at the head of the Tiger Creek conduit.

The conduit from the regulator to the forebay has a capacity approximately 25 per cent in excess of the conduit from Salt Springs and will deliver 625 cu. ft. per sec. (17.7 cu. m/s.) into the Tiger Creek forebay. This forebay is entirely an artificial pond and was created by excavating the top of a knoll on the ridge above Tiger Creek power house. About 200,000 cu. yd. (153,000 cu. m.) of material was moved to provide a forebay of 40 acre-ft. (49,500 cu. m.) capacity. About thirty minutes are required for water released at the regulator to reach the forebay and the available capacity in the forebay is sufficient to provide peaking during this interval.

Automatic gates are provided at the outlet of the regulator to maintain a constant flow in the conduit. These gates operate from a float control mechanism which will maintain a constant level of water in the conduit regardless of the height of water behind the gates discharging into the canal. The controls have been carried to the switchboard room in Tiger Creek power house and the operator may adjust the floats at the regulator to maintain any desired level of water and consequently any rate of flow between the regulator and forebay. The design of this automatic gate control equipment was perfected several years ago in connection with the control of water discharged from the afterbay at Pit River power house No. 3 where it was necessary to maintain the flow in Pit River below the power house at an amount equal to the natural flow in the river at that season of the year and at the same time permit peaking of the plant. No difficulty whatever has been experienced in the operation of this equipment and it has performed in every respect exactly as planned. Therefore, much confidence is placed in the ability of the operator at Tiger Creek power house to maintain complete and accurate control of the water being fed from the regulator into Tiger Creek forebay.

Tiger Creek Power House

From the forebay above Tiger Creek power house, water enters the penstock which consists of a single steel pipe 4,750 ft. (1,448 m.) in length varying in diameter from 102 in. (2.59 m.) at the top to 72 in. (1.83 m.) at the wye outside the power house. About 4,000 ft. (1,220 m.) of the upper portion of the pipe is of riveted steel with rivets countersunk on the inside of the pipe. The lower portion is of seamless pipe. At the wye the pipe branches into two 52-in. (132.08 cm.) diameter lines and again into four 36-in. (91.44 cm.) diameter lines, a separate line leading to each of the four impulse wheels of the two double overhung units in the power house.

Tiger Creek power house is the controlling station for the 220-kv. transmission lines constructed to receive the power generated by the waters of the Mokelumne

Fig. 5—General View of Tiger Creek Power House and Mokelumne River

River and transmit it to the load centers at Newark and Herndon. To charge the 109 mi. (175 km.) of 220-kv. line between Tiger Creek and Newark requires approximately 25,000 kva., which made it desirable that the minimum capacity for each generator be not less than this amount in order that a single unit could charge the transmission line. Experience has indicated that it is much better to be able to charge a transmission line with a single unit than to attempt this function with two units in parallel. The extremely low excitation of the generator at times of charging an unloaded transmission line renders the parallel operation of generators unstable and makes their control exceedingly difficult. For this reason plant operation is very greatly facilitated if a line which is taken out of service

for any reason, can be charged from a single unit. Also it renders unnecessary the unloading of a second unit in order to make it available for line charging purposes. The static head and water quantities available at Tiger Creek indicated that this plant should have installed in it approximately 60,000 kva. in generator capacity and it was, therefore, at once evident that a two-unit layout was the proper one.

Each waterwheel unit was designed to deliver 36,000 hp. at 225 r. p. m. under a net effective head of 1,190 ft. (362.71 m.), each of the overhung impulse wheels being rated at 18,000 hp. The generators are rated 30,000 kva., 11,000 volts, 60 cycles, 85 per cent power factor. These waterwheel units are well up towards the maximum size practical for the head and water quantities available at Tiger Creek and in physical dimensions rank among the largest impulse wheels ever constructed.

Many refinements have been incorporated in the design of the wheels. A straight flow needle nozzle has been designed which introduces a minimum disturbance in the water flow, thus giving a uniform, compact jet

FIG. 6—INTERIOR SALT SPRINGS POWER HOUSE

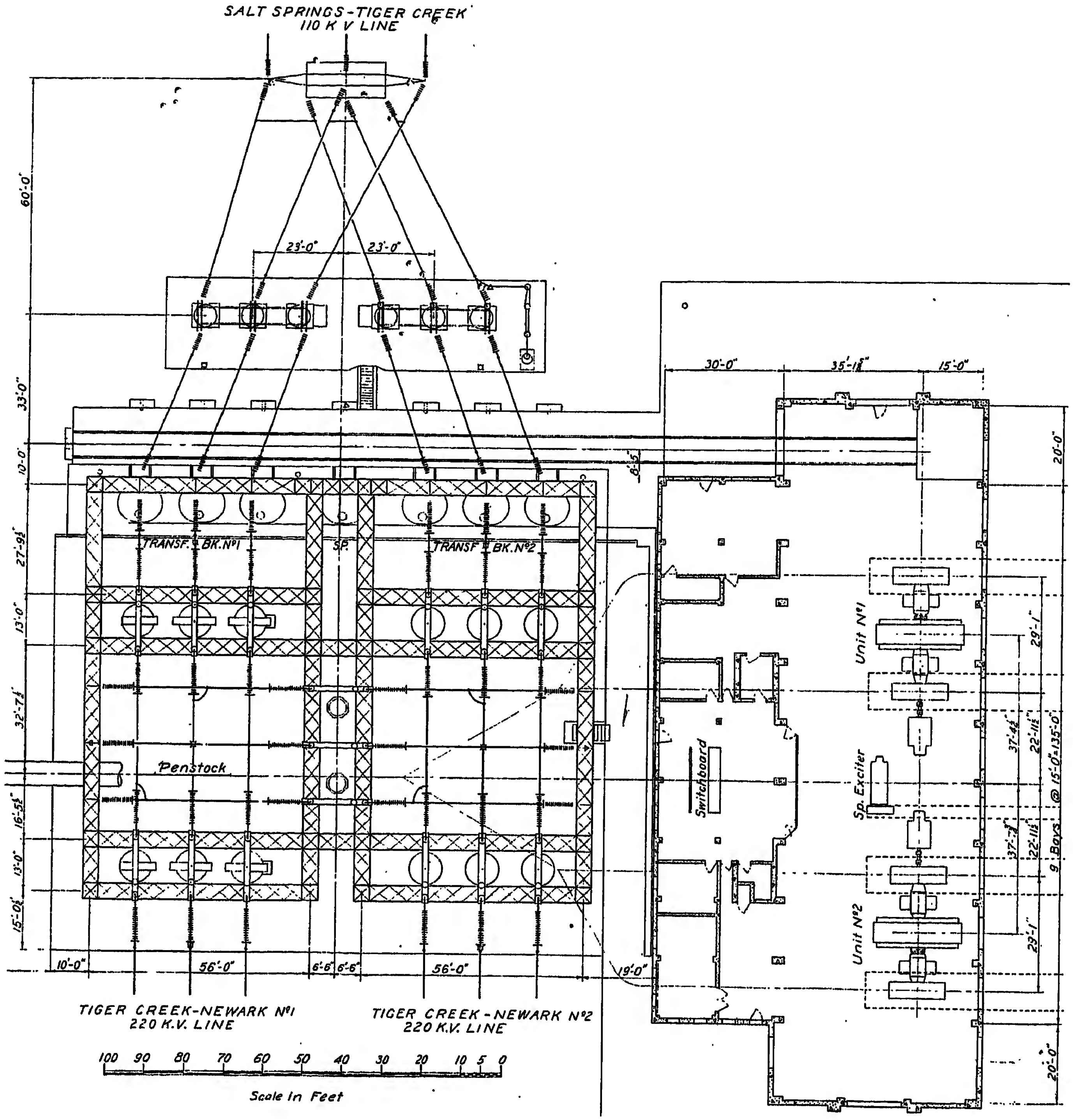
delivering maximum power to the waterwheel buckets. The power needles are operated by the governor servomotors and are arranged for slow closure upon load rejection as a water conservation measure in much the same manner that the relief valve closes on a large hydraulic turbine installation. Linked with the governor and needle operating mechanism is a jet deflector or stream bender in the form of a collar surrounding the jet which operates to remove water from the wheel instantly upon load rejection. The combination of jet deflector and slow closing needle is ideal for an impulse wheel installation in that it makes it possible to divert the water from the wheel quickly without disturbing the flow in the penstock with its attendant surge. This permits economies in the installation through reduced penstock cost and the omission of a surge chamber.

Simplicity of plant layout was the aim throughout the design of Tiger Creek power house. Each generator with its associated step-up transformer bank is considered as a unit and there is no oil circuit breaker between the generator and the low-voltage side of the transformer. The electrical connections are extremely simple. A steel bus structure containing four 11-kv. truck type oil circuit breakers is installed in the bus room. Two of the oil circuit breakers serve to connect the generators to an 11-kv. bus for the purpose of synchronizing before closing the main 220-kv. breakers. When the units are in parallel on the high-voltage side of the transformers one of these breakers is opened separating the units on the generator side, the other remaining closed to supply power for station requirements. The remaining two truck type breakers are for the station power transformer bank. As was the case at Salt Springs power house, these station power oil circuit breakers are made interchangeable with the main breakers, thus providing spare oil circuit breaker equipment.

Each generator is provided with a direct-connected exciter and pilot exciter which are controlled by voltage regulators. A spare exciter set is installed between the main generating units and arranged to be driven either by an impulse waterwheel or an induction motor. Each waterwheel has its individual governor oil pressure system with duplicate oil pumps. One pump is motor-driven, the other driven by a small impulse wheel. For normal operation the motor-driven pump maintains the oil pressure, but suitable controls have been provided so that any failure of supply from the motor-driven pump will automatically start the water-driven pump to reestablish governor oil pressure.

The switchboard is located in the switch and bus section of the power house on the level of the generator floor and midway between the units. All equipment requiring frequent attention has been installed on the main power house floor to facilitate operation and considerable thought has been given to the convenience of the location of equipment from an operating standpoint. Equipment which requires infrequent inspection has been placed on the second floor of the power house and the general layout of the plant has followed the idea of making it possible to operate with a small personnel. The normal shift will consist of a first and second operator, the first operator's duty being at the switchboard, with the second operator available for oiling and the operation of the hand-operated high-voltage disconnecting switches in the outdoor switch yard.

The step-up transformers consist of two main banks with one spare unit arranged for physical interchange in case of damage to an operating unit. These transformers are provided with combined two-winding and auto-transformer windings. The auto-transformer winding has a rating of 10,000 kva. per unit and will step the incoming power from Salt Springs power house from 107.5 to 215 kv. The tertiary winding has a rating of 10,000 kva. per unit, giving 30,000 kva. per bank, sufficient to care for one Tiger Creek generator. The transformer banks, therefore, will have a capacity of 60,000 kva. each, 30,000 kva. for one Tiger Creek



Plan of Tiger Creek Power House and Bus Structure

unit and 30,000 kva. from Salt Springs. Each bank is capable of carrying the normal Salt Springs output as well as the output from one Tiger Creek unit.

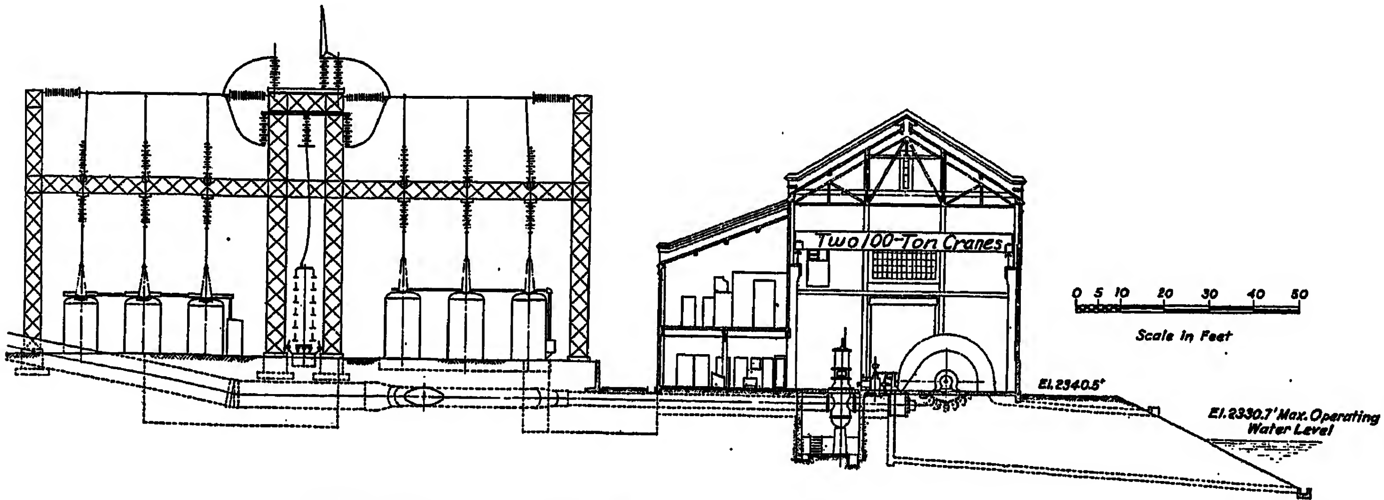
In order to re-regulate the water discharged from Tiger Creek plant for diversion to the next lower plant an afterbay has been provided. This was formed by the construction of a concrete arch dam about 100 ft. (30.48 m.) in height in the Mokelumne River, some 2 mi. (3.2 km.) below the plant. This dam creates a reservoir with a flooded area of about 100 acres (400,000 sq. m.). The top 3 ft. (91 cm.) of this pond, with a capacity of 300 acre-ft. (370,000 cu. m.) will be used to re-regulate the Tiger Creek peaks as well as some of the irregularities in the natural run-off tributary to the lower plant which are not controlled by the storage on the system.

West Point Power House

The last of the four power houses to be constructed on the Mokelumne River, but the one immediately downstream from Tiger Creek will be known as West Point power house. The existence of the present Electra

power house has influenced the location and construction of this plant and it will be necessary to make brief mention of the factors involved.

At the present time Electra is supplied with water through two conduits known as the Upper Standard Canal and the Lower Standard Canal. The lower conduit was constructed during the early mining days and delivers water into Lake Tabeaud which forms the forebay for Electra power house. At a later date the upper conduit was constructed, some 200 ft. (61 m.) higher in elevation than the lower conduit and terminating in Petty reservoir, an enlarged section of the conduit forming a second forebay at Electra with 200 ft. (61 m.) extra head. The combined capacity of these conduits is approximately 210 cu. ft. per sec. (5.95 cu. m/sec.). Both have grades of 2.5 ft. (76.2 cm.) per 1,000 ft. (304.8 m.) for flumes and 1.5 ft. (45.7 cm.) per 1,000 ft. (304.8 m.) for ditch sections which are excessive for the enlarged capacity now contemplated. The construction of a new conduit above the existing conduits has several disadvantages, the most important of which are the lack of a forebay site at the Electra end and the impossibility of keeping the conduits free from debris while excavating a new location immediately above. The plan finally adopted for the development of this head was to build a new conduit below the two existing canals beginning at the high water level of Tabeaud reservoir and rising on a grade of 0.8 ft. (24.38 cm.) per 1,000 ft. (304.8 m.) until the grade line intersects the river gradient. This new conduit will be about 13.7 mi. (22 km.) long, intersecting the river in the vicinity of the West Point road crossing and about 4 mi. (6.4 km.) below Tiger Creek afterbay dam. It will have a capacity of 575 cu. ft. per sec. (16.28 cu. m/sec.). An advantage of this plan is that the existing canals and power house may be operated without interference during the period of construction of the conduit. At the time construction is started on West Point, the new Electra will have been completed thus diverting water from the river into the new conduit and freeing the Upper Standard Canal for construction work.



Section Through Tiger Creek Power House Parallel to Penstock

The diversion of water for West Point will be made from Tiger Creek afterbay about 3 ft. (91 cm.) from the top of the dam and will follow roughly the location of the present Upper Standard Canal for about 4 mi. (6.4 km.) where it will join the West Point penstock. No forebay facilities being available, the plant will be designed to operate at 100 per cent load factor. The static head will be about 285 ft. (86.87 m.) and the maximum flow 575 cu. ft. per sec. (16.28 cu. m/sec.). The installation will consist of a single vertical turbine driving a 15,000-kva., 11,000-volt generator and the plant will be laid out for full automatic operation with certain controls carried back to Tiger Creek power house. The generated power will be stepped up to 60 kv. to supply the demands now served by the present Electra plant. West Point power house will be the only plant on the Mokelumne System not regularly feeding into the 220-kv. transmission system. Provision will be made at Electra however to absorb this power into the 220-kv. system at such times as there is available sufficient energy at 60-kv. from another source to make the output from West Point in excess of requirements. A 60-kv. wood pole line will be constructed from West Point to Electra to tie in with the existing 60-kv. lines.

Electra Power House

Construction of the new Electra power house and conduit will follow immediately upon the completion of the Salt Springs-Tiger Creek development, probably in the fall of 1931. The static head to be developed at Electra is 1,265 ft. (385.57 m.) and the water flow 575 cu. ft. per sec. (16.28 cu. m/sec.). The head and water quantity are so nearly the same as at Tiger Creek that the plant will be almost an exact duplicate. The two waterwheels will have a slightly greater horsepower

rating being designed for 37,500 hp. each at 225 r. p. m. but will have almost identical physical dimensions which will permit the construction of a duplicate power house. One factor is present in the Electra designs which was absent at Tiger Creek and that is the presence of an excellent forebay in Lake Tabeaud with a capacity of 1,158 acre-ft. (1,428,000 cu. m.). This will permit of considerable peaking at Electra and all designs are being made so that a third unit for peaking purposes may be added at a later date if economies and system load requirements point to the desirability of its installation.

Power generated at Electra will be stepped up through two banks of transformers to 220-kv. for connection to the Tiger Creek-Newark transmission lines. It will also be necessary to provide for supplying power to the 60-kv. and 17-kv. systems now taking the output

FIG. 7—GENERAL VIEW SALT SPRINGS POWER HOUSE

Showing penstock (one for turbine and one for by-pass) tail canal and Tiger Creek conduit main quarry (upper right) for dam material and gorge of the Mokelumne River

from the present plant. As pointed out above, this demand will normally be met by West Point power house.

The old Electra power house will be continued in operation during the construction of the new power house and upon completion of the new plant will be completely demolished. There is a remarkable contrast between the thirty-year old pioneer plant and its modern successor and brief mention of the old plant will be of interest.

The power house is built of corrugated iron on a steel frame and houses seven generating units, five 2,000-kw. Stanley inductor type generators and two 5,000-kw. Stanley revolving field generators. Excitation is at 70 volts and the generator voltage is 2,300, three-phase, 60 cycles. The five 2,000-kw. units are set quite close together with their shafts at an angle of 45 deg. with the main axis of the generator room. The 5,000-kw. units are installed with their shafts parallel to the long axis of the room. Power is stepped up through six main banks of Stanley single-phase transformers, five banks feeding into the 60-kv. transmission system and the sixth bank furnishing 17-kv. power to the gold mines along the Mother Lode.

The 20,000-kva. installation, which at one time was one of the important hydroelectric plants of the country, is now completely obsolete and will be scrapped in its entirety. In its place will stand a modern steel frame, reinforced concrete building housing two generating units each of which is capable of delivering one and one-half times as much power as the combined output of the seven replaced units. The transmission voltage has risen from the 60-kv. record of 1902 to the 220-kv. commonplace of thirty years later giving marked evidence of the rapid changes in the art.

GENERAL

The peak load on the system of the Pacific Gas and Electric Company and associated companies reached 853,300 kw. in July, 1930. In the decade from 1920 to 1930 the load on the system has grown at the average annual rate of 7.25 per cent, which has required the addition of some 40,000 kw. of new generating capacity each year to keep pace with the demand for power. Part of the new capacity has consisted of steam-driven units and part of hydro units, the ratio of the two types of prime movers for the entire system up to 1930 standing at approximately two to five.

Prior to the advent of natural gas into the fuel market of Central California, and the greatly increased steam plant economies recently secured, hydroelectric plants, including their relatively long transmission lines, had been able to deliver power to the consumer at prices which made the development of the hydro resources of the state very attractive from an economic standpoint. The picture has been altered somewhat and natural gas has now placed the cost of power from the two sources approximately on a par. A relatively small change either way in the cost of fuel may have a very large influence on the type of future generating equipment installed.

The power peak growth of the system for the next five years will approximate 50,000 kw. annually. This is favorable to hydroelectric development in that it permits full development of a river over a short period of time, thus spreading the cost of water storage facilities over all of the plants on the stream and reducing the fixed charges per kw. hr. generated. In order to produce hydroelectric power on the most economical basis, hydro plants in California must operate on the highest possible load factor. The average annual load factor for the system of the Pacific Gas and Electric Company is approximately 62 per cent and all studies for the plants on the Mokelumne River, with the exception of the 100 per cent load factor plant at West Point, were on the basis of 85 per cent load factor.

Such a condition of operation will be possible in all years with normal or above normal rainfall. Studies of run-off over a 24-year period have indicated that the average annual output will be 88 per cent of the maximum possible during the wettest year recorded with a 47 per cent output during the extreme dry year. Normal operation of the plants on the Mokelumne River will be on base load with system peaks carried by steam. This condition may be reversed in extreme dry years when the economic use of stored water dictates its use for the carrying of peak loads.

The total cost of the Mokelumne River Development as outlined herein, including transmission and the increased capacity at Newark Substation, is to the order of $39,000,000.00. The entire design and construction of the project have been carried out by the regular personnel of the Pacific Gas and Electric Company.

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Tie-Line Control of Interconnected Networks

BY T. E. PURCELL[1] and C. A. POWEL[2]
Non-member Member, A. I. E. E.

Synopsis.—The paper describes operating experience with tie-line load regulators on the tie connecting the Colfax Power Station of the Duquesne Light Co. and the Springdale Station of the West Penn Power Co. A description is given of the equipment used and also of supplementary equipment, such as program loading equipment installed at Colfax to maintain the most economic division of load between the various generating units. A new hydraulic speed changing device intended to reduce wear on the governor parts to a minimum is also described. Tests made jointly by the Duquesne Light and West Penn Power Companies to determine the effect of operating frequency and tie-line regulators simultaneously are discussed and the curves giving the results are shown.

Introduction

THE electrical industry has been successful in continually rendering a more reliable service at a lower cost to its customers. To do this it has been necessary to decrease both capital expenditures and operating cost per unit of system capacity and at the same time provide power systems less susceptible to service interruptions. One thing which has contributed in a great measure to this progress has been the connecting together of power systems in such a manner as to make available to the several systems embracing large areas the economies resulting from the better use factor of both generating and transmission plants, the operation of fewer of the older and less efficient equipments, and the diversity of peak loads. A casual survey is sufficient to reveal that this so-called interconnection is still relatively new and that the immediate years to come will witness a most extraordinary development in this phase of the industry.

Utility officials recognizing the economies resulting from exchange of power from system to system are arranging cooperative or joint operation in a manner to leave no obstacles in the way of the operating man to the end that the greatest number of kilowatt-hours may be produced and delivered to the customer at the lowest cost and with the greatest reliability. A few years ago an interconnected power system embracing more than a few thousand square miles was the exception, whereas today for instance, the power systems between Boston, Chicago, and New Orleans may be formed, when occasion arises for exchange of power, into one continuous interconnected system.

This parallel or interconnected operation of several power systems has brought to the fore a new and most important problem, namely that of controlling the interchange of power between the several systems. This problem first came into prominence under the name of frequency control and many engineers attacked it from that point of view. As a matter of fact it is one of load control and little has been done towards its solution. The division of power in a loop under the control of phase shifting equipment is a related problem but should not be confused with the control of total interchange by the prime mover governors. An attempt to regulate two or more interconnected systems with an automatic frequency regulator on each will promptly develop the fact that the load variations on the systems will be so dissimilar that regardless of frequency control, the power flow over the tie lines cannot be regulated. In fact it has been observed in some cases that when the bulk of the load change falls on one system, the power flow over the tie line exceeds the load change by the amount required to accelerate or retard the systems.

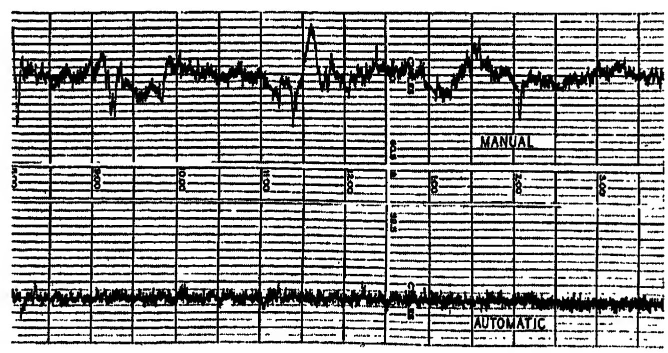

FIG. 1—MANUAL AND AUTOMATIC FREQUENCY CONTROL CHARTS AT COLFAX. (SYSTEMS NOT INTERCONNECTED)

The Duquesne Light Company, having recognized several years ago that the problem was one of load control rather than one of frequency control, enlisted the cooperation of several manufacturers in an experiment with automatic control of the tie line connecting the Duquesne Light Company having a normal capacity of 360,000 kw. with the West Penn Power Company whose interconnections form a network of more than 4,000,000 kw. capacity. The tie which is between the Colfax Station and the Springdale Station of the West Penn Power Company is rated 36,000 kva. at 132 kv.

In addition to the control of power over the tie line it has also been desirable to maintain frequency within a very close range. The control of frequency in itself has been found possible through the use of automatic equipment, and is a comparatively simple problem.

1. Duquesne Light Co., Pittsburgh, Pa.
2. Gen. Engr., Westinghouse Elec. & Mfg., Co., East Pittsburgh, Pa.

Presented at the Pacific Coast Convention of the A. I. E. E., Lake Tahoe, California, August 25-28, 1931.

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Fig. 1 illustrates system frequency with and without automatic control.

The maximum economy possible as a result of interconnection will not be obtained unless the most efficient loadings of the several generating units on the interconnected system are closely adhered to. This loading must be anticipated and must take account of the distribution of the load, the inherent efficiency of the generating station and units, and numerous other factors. This economy cannot be obtained with manual control, and to obtain the greatest advantage the control must be automatic. Such control must be simple, reliable, and accurate and must be susceptible to being readily set for any division of load between the generating units which may prove advantageous.

Automatic load control over the tie line and automatic control of the output of the generating units in accordance with a predetermined program, both being supervised by or subservient to automatic frequency control, have been in successful operation at the Colfax Power Station for some time. This equipment has been developed as a result of considerable research work both by the Duquesne Light Company and two manufacturers whose equipment is in use. While no doubt many improvements are yet to be made, the operation exceeds expectations held at the time the work was started some two years ago.

Performance of a tie line connecting two large power systems involves the rate of load change, inertia, and sensitivity of the prime mover governors, along with the electrical characteristics, such as amount of reactance in the tie lines connecting the two systems. A load change on one system causes a redistribution of the load between the various prime movers, and also a transient distribution which occurs during the period of adjustment to the new load. This transient condition is not noticeable in a closely tied system such as the average metropolitan utility. However, if there is only one tie line connecting two systems, these load transients are concentrated and assume considerable importance. The majority of load changes occurring on the West Penn tie line connecting the Colfax and Springdale Stations are of a transient nature of rather short duration.

The prime requirements of a successful tie line load regulator are that it must not respond to these small transient load changes, but it must respond to small sustained changes. In addition it must respond to large load changes whether temporary or sustained.

Tie-Line Load Regulators

The Westinghouse Company has developed two types of control equipment. The first type was devised primarily to eliminate corrective action due to transient changes, but to respond rapidly to load changes of reasonable magnitude. This type of load control shown schematically in Fig. 2 consists essentially of two solenoids responding to watts. These coils are connected in A and C phases and are shown as C and D. They are arranged to assist each other in balancing the arm E which has a movable weight F riding on it. The action of the regulator is as follows:

With the weight F immediately above the fulcrum, the arm E is balanced and requires zero watts in the coils to maintain a balance. Any power flow through the coils will cause the arm E to "raise" or "lower" depending upon the direction of the power. For small changes in load the contact J engages either the raise or lower stationary contacts R or L. These contacts send an impulse to the governor motor through time delay relays, which are adjusted to delay the impulse approximately 2½ seconds after the contacts have closed. Experience has shown that on the West Penn tie line the periods of the transient load swings have a shorter period than two seconds. An oscillation occurring on

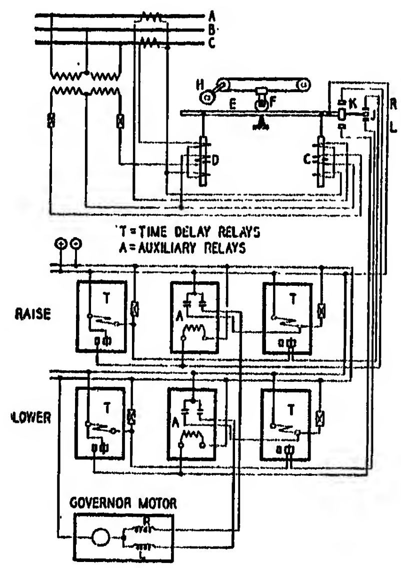

Fig. 2—Westinghouse Solenoid Type Automatic Tie-Line Regulator

a tie line will cause an unbalance and close the "raise" or "lower" contacts. If the period of contact engagement exceeds the 2½-second time delay a correction is made accordingly. If the period of the contact engagement is less than 2½ seconds no correction results.

A second set of time delay relays is provided to limit the length of impulse delivered to the governors to a predetermined value.

The part of the regulator described above takes care of the first requirement very satisfactorily. To take care of large changes in load, a second set of contacts K is provided which operates the speed changer motor directly through the auxiliary relays without time delay. The contacts K are set to close for approximately 10,000 kw. change in load, but hunting of the regulator in this zone is prevented by the opening of these contacts at ± 5,000 kw. Below this value the auxiliary contacts J are relied upon to return gradually the line load to normal.

This device has shown considerable promise in that it does not cause corrections to be made which must immediately be counteracted by reverse corrections.

A large change of turbine loading to counteract load in a tie line results in considerable energy being supplied to the system to accelerate it while changing the phase angle relation across the tie line. It can be seen that after the phase angle is changed this energy is still available to supply load, which results in an overshooting of the proper value. It is essential that any regulator responding at a rapid rate must have a wide zone

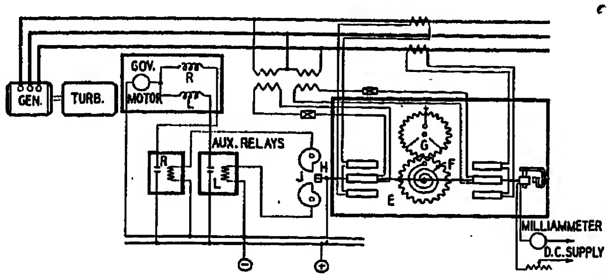

Fig. 3—Westinghouse Kelvin Balance Type Automatic Tie-Line Regulator

about the final position in which the load corrections are made in small increments.

The above regulator is not well adapted to remote control, and for this application another design utilizing a Kelvin balance has been developed. This regulator has a calibrated spring *F* (Fig. 3) attached to a geared disk *G* which allows the torque due to the power in the Kelvin balance to be neutralized by rotating the disk *G* to the right or left, so that a balance can be made at any load within the limits of the spring *F*. A motor-driven cam mechanism is arranged to make contact intermittently with the contacts *H* and check the position of the Kelvin balance *E*. Variations in load cause the Kelvin balance to deflect the contact *H* which through suitable mechanism makes contact with the cam *J* thus routing the "raise" and "lower" impulses to the governor motor.

It can be seen that as the unbalance decreases the period of contact engagement with the cams decreases and the duration of the impulse to the governor motor also decreases thus providing an anti-hunting feature. Disk *G* can be rotated by a position transmitter, or a D'Arsonval element can be attached to the lever *E* to counteract the torque in the Kelvin balance, making the device readily adapted to remote control.

No time delay relays are used with this device. It will cause more corrective impulses to be delivered to the governor motors than the device first described and it is somewhat slower in correcting large errors due to rapid changes of load. It will, however, maintain a closer integrated load under average conditions.

The solution of the problem of tie line control offered by the Leeds and Northrup Company consists essentially of a master element comprising a thermal converter and a load setter. The thermal converter is similar to the Lincoln thermal demand meter, except that instead of using a bi-metal strip to indicate the kilowatt load, thermocouples are inserted which produce a potential for transmission to suitable receiving apparatus.

The thermal converter is indicated at *C*, Fig. 4. The load setter is a potentiometer with a calibrated dial, and is adjusted to give a potential equal to the thermocouple potential of the thermal converter for a given tie line load. These two potentials are connected in opposition through a sensitive galvanometer in the load controller. This galvanometer is similar to the Leeds & Northrup Company temperature recorder, and deflects in proportion to the difference in potential between the load setter and the thermocouples of the thermal converter.

The unbalance indicated by the galvanometer is checked by the cam mechanism shown at *F*, which delivers a corrective impulse to the turbine governors in proportion to the load error. This device tends to change the turbine loads until the tie line load flowing through the thermal converter sets up a potential equal to that of the load setter. This control gives very satisfactory operation.

Program Load Control

In the past where frequency control has been adopted, it has been common practise to do all the regulating in one station and usually on one unit. Where the regulating device was put on more than one unit, it was found that the division of load between units was liable

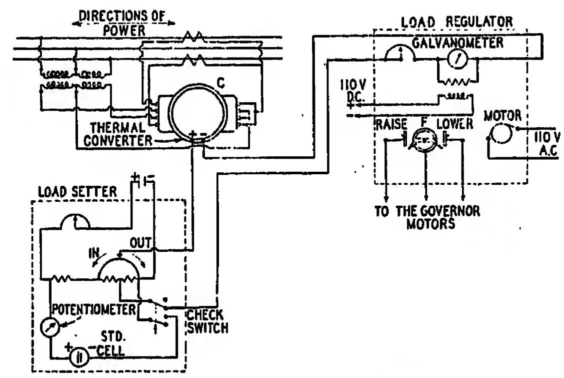

Fig. 4—Leeds and Northrup Potentiometer Type Automatic Tie-Line Regulator

to be erratic. Therefore load balancing schemes were devised to force the various units to take their proper share of load increments.

These devices are relatively simple and perform satisfactorily, but the principle of dividing up all load increments proportionally between units in a steam station does not necessarily make for maximum efficiency. Most operators have considered the output of the machine and have not taken into account the inefficiency due to operating with steam control valves in a throttling position. In the equipment developed by the Westinghouse Company in accordance with the

requirements established by the Duquesne Light operators, load scheduling is based on turbine valve positions, rather than on generator output, thus maintaining each turbine at its most efficient valve opening regardless of the effect of the many variables which enter into the position of the valve with reference to the load.

Fig. 5 shows a schematic diagram of the equipment used to obtain automatic division of load in accordance with the predetermined program loading at the Colfax Power Station. The capacities of the generating units in this station are as follows:

Unit No. 1	60,000 kw.
Unit No. 2	60,000 kw.
Unit No. 3*A*	30,000 kw.
Unit No. 3*B*	30,000 kw.
Unit No. 4*A*	41,250 kw.
Unit No. 4*B*	41,250 kw.

On the larger steam turbines the nozzles are usually grouped in three groups, each fed from the primary, secondary, and tertiary valves. These valves are equipped with auxiliary switches to establish the proper sequence of loading. Referring to Fig. 5, the motor-operated selector switch routes the "raise" or "lower" impulses from the tie-line load regulator through the load scheduling device to the turbine governors. In order to simplify the description and diagram as much as possible only two machines have been shown each with a primary and secondary valve.

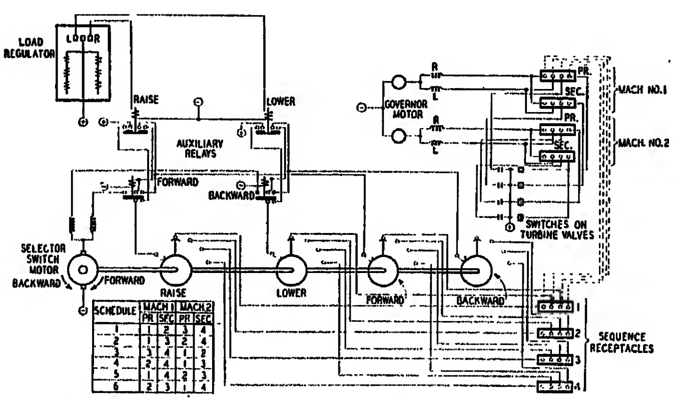

Fig. 5—Westinghouse Program Load Controller

There are six loading schedules as shown in the table and in order to set up any one of these schedules, a system of receptacles and plugs is used. There are four machine receptacles and four sequence receptacles. The selector switch has four independent contact arms, two of which are used for routing the raise or lower impulses and two for the control of the selector switch driving motor. The position of the selector switch is determined by the position of the valve auxiliary switches and also by the way in which the machine and sequence receptacles are connected by jumpers. For example consider that machine No. 1 primary receptacle is connected to sequence receptacle No. 1, No. 1 secondary to sequence 2, No. 2 primary to sequence 3 and No. 2 secondary to sequence 4 receptacles. The operation would then be as follows with both machines carrying minimum load and the selector switch in position No. 1: On increasing the load, the load regulator makes the raise contact and the raising impulse is routed through to No. 1 governor motor. After the load has increased to the point where the primary valve is wide open, the primary valve auxiliary switch makes contact which energizes the forward control of the selector switch driving motor on the next raising impulse. The selector switch rotates in the forward direction until cut off by the forward contact breaking the circuit with the first contact. The width of the forward and backward contacts are such that the motor will drift to the next position after the control circuit is broken. The switch is now in position No. 2 and the raising or lowering impulses are still routed to No. 1 governor motor. In the same manner, the selector switch transfers to the next position after the secondary valve on machine No. 1 fully opens. On decreasing load, the selector switch returns, the motor being energized by a circuit through the "backward" selector switch arm and the valve switch contacts which make when the valves are closed. The forward and backward auxiliary relays seal in so that the motor-selector switch travels at least one position and also breaks the control circuit from the regulator so that control is broken during the transfer.

Fig. 6 is a rear view of the program load control panel, showing the 32 receptacles and jacks. One row of receptacles represents the 16 valves on the six turbo-generators and the other row represents sequence positions, these being numbered 1 to 16. By inserting the jacks in the proper receptacles any desired sequence of load scheduling can be obtained. The motor-operated selector switch is at the right. The master raise and lower contactors are at the top of this panel. On the front of the panels are mounted the relays and necessary control and transfer switches.

Hydraulic Speed Changer

Changing the speed or load on a turbine controlled by the usual flyball governor is accomplished by increasing or decreasing the tension on the speed changer spring. The tension on this spring is approximately 1,000 lb. with the governor in full load position and the standard mechanical speed changer has heretofore carried this load under normal operating conditions without appreciable wear.

The introduction of frequency control, however, which called upon the speed changer to respond as often as 30 impulses in a minute, made it necessary to remove the spring load from the speed changer parts in order to prevent excessive wear, and for this purpose a hydraulic speed changer was developed and has been in successful operation for some time.

The hydraulic speed changer shown in Fig. 7 consists of an oil-operated piston, A, carrying the load of the spring, B, a relay C within the piston to control its position, a motor-operated speed changer mechanism D for adjusting the oil relay, and mechanism, E, to control the governor position by hand in case of failure of the oil pressure.

The relay controls the position of the operating piston by means of four discharge ports. On the up stroke of the relay, oil supplied through an orifice to the upper face of the piston is discharged through the piston to the drain. On the down stroke of the relay the discharge ports are closed, the oil pressure builds up on top of the piston which then follows the movement of the relay. The relay travel in the operating piston is restricted to 1/8 in. in either direction so that in case of oil-pressure failure, the spring load can be taken by the relay itself with only 1/8 in. change in the spring length.

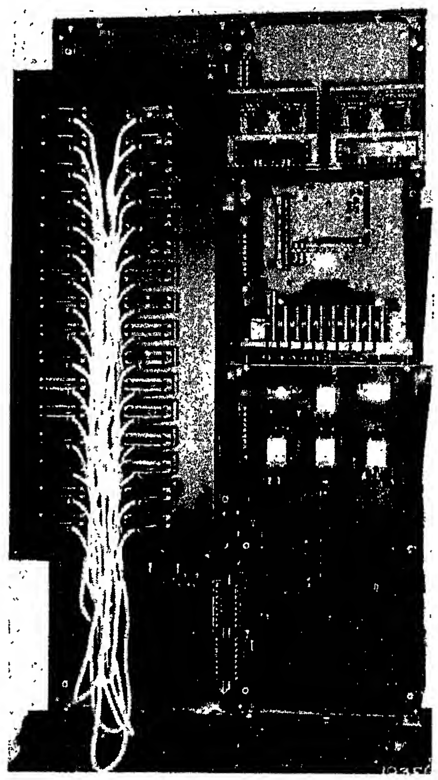

Fig. 6—Rear View of Program Load Controller Showing Plug Receptacles for Arranging Loading Sequence

The relay is moved up and down by a rotating nut actuated either by the speed-changer motor or by the handwheel and is prevented from turning by a key.

The motor-mechanism worm gear is locked to the nut by two long sliding pins, so that the worm wheel housing and nut rotate as a unit. For hand operation the hand wheel is lowered, disengaging the sliding pins, and permitting the handwheel to operate the oil relay independently of the motor mechanism.

The relay controlling mechanism is submerged in oil, which is kept at a constant level by a drain pipe, and is supplied with oil by the discharge from the relay. Since the rotating parts of the mechanism are well lubricated and are not loaded with the spring tension, they are free to respond to a short contact of the tie-line load regulator. To prevent the motor from overtraveling a magnetic brake is provided.

All generating units on the Duquesne Light Company's system on which automatic control, either of the frequency or load type, is used, will be equipped with a speed-changing device of this character.

Operating Experiences with Tie-Line Load Control

The instantaneous speed of any system is a function of the system load and the setting of the turbine governor. Thus, with any given setting the speed of the system will vary as the load changes. If two systems are interconnected through one or more lines, the speed of the entire interconnection becomes a function of the governors and the total load, and the generator load on one system does not bear a direct relation to the demand on that particular system. The generator load being a function of system speed requires that the excess demand be supplied through the interconnecting tie lines. If the two systems under control are of the same size and have approximately the same load characteristics, it is possible to remain in parallel for reasonable periods of time without overloading the tie lines when operating on straight speed-governor control. It is customary when such an interconnection exists for the system controlling the tie line to adjust its governors to maintain 60-cycle frequency if this correction will tend to correct the tie-line loading.

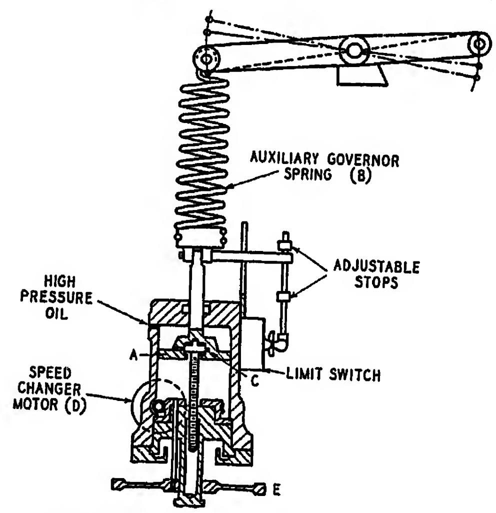

Fig. 7—Westinghouse Hydraulic Speed Changer

With frequency control on one system, it is evident that all of the load changes occurring on the entire interconnection will eventually appear on the units under automatic control, so that all the net load changes of the system without frequency control will appear in the tie line.

Observation on the Colfax-Springdale tie line for a period of two years has shown the above reasoning to be correct. Difficulties were found in maintaining an exchange of power between the systems when it approached the amounts contracted for. The variations in load appearing on the tie line required almost constant supervision of the loading, and the situation was aggravated with the addition of frequency control on the West Penn Power system. Fig. 8 shows typical tie-line load and frequency charts during manual control.

It is generally assumed that tie-line load control tends to make frequency control more difficult to obtain. This is based on the assumption that load changes on one system must all flow over the tie line and be compensated for by the frequency-control equipment before the tie-line control equipment has functioned. That is to say, the load change is first corrected by the frequency regulator and later corrected by the tie-line control, which in turn requires the dropping by the frequency regulator of load equal to the amount picked up by the tie-line load control. This reasoning would be sound if the frequency-control equipment were very much faster in response than the tie-line regulator. As a matter of fact experience has shown that the two types of control work satisfactorily together, although possibly at the expense of increased frequency of operation during periods when corrections must be made by one control to compensate for the operation of the other.

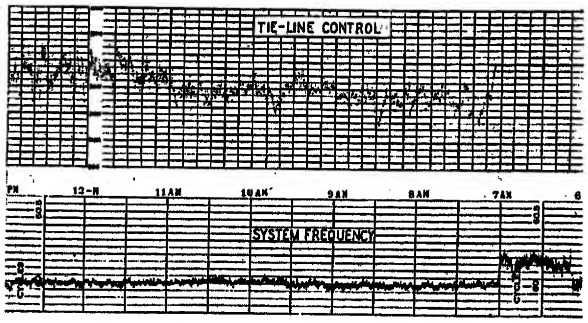

FIG. 8—TIE-LINE LOAD WITH MANUAL CONTROL AT COLFAX AND AUTOMATIC FREQUENCY CONTROL AT WINDSOR

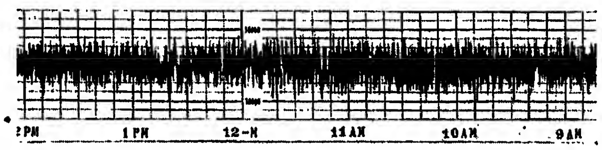

FIG. 9—TYPICAL CHART SHOWING TIE-LINE CONTROL WITH REGULATED FREQUENCY AT WINDSOR

It has also been observed that the use of tie-line regulators affects the permissible neutral zone of the frequency regulators on the interconnected systems. The initial installation of tie-line load control at Colfax was made at a time when the West Penn Power Co. was maintaining frequency within plus and minus 0.05 of a cycle by means of automatic-frequency control devices at the Windsor Power Station. Later in order to reduce the overloading of other tie lines the frequency was allowed to vary as much as plus and minus 0.15 of a cycle. This resulted in a more erratic power flow over the tie line and an increase in corrective operation of the tie-line regulator. Fig. 9 shows a tie-line

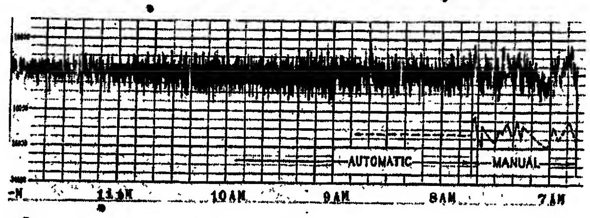

FIG. 10—MANUAL AND AUTOMATIC TIE-LINE CONTROL
Broken Line Shows the Average of the Load Swings

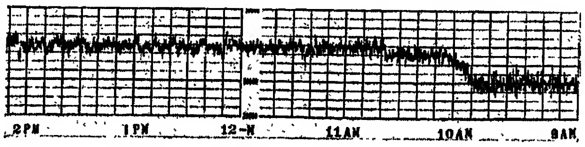

FIG. 11—AUTOMATIC TIE-LINE CONTROL UNDER LIGHT LOAD CONDITIONS

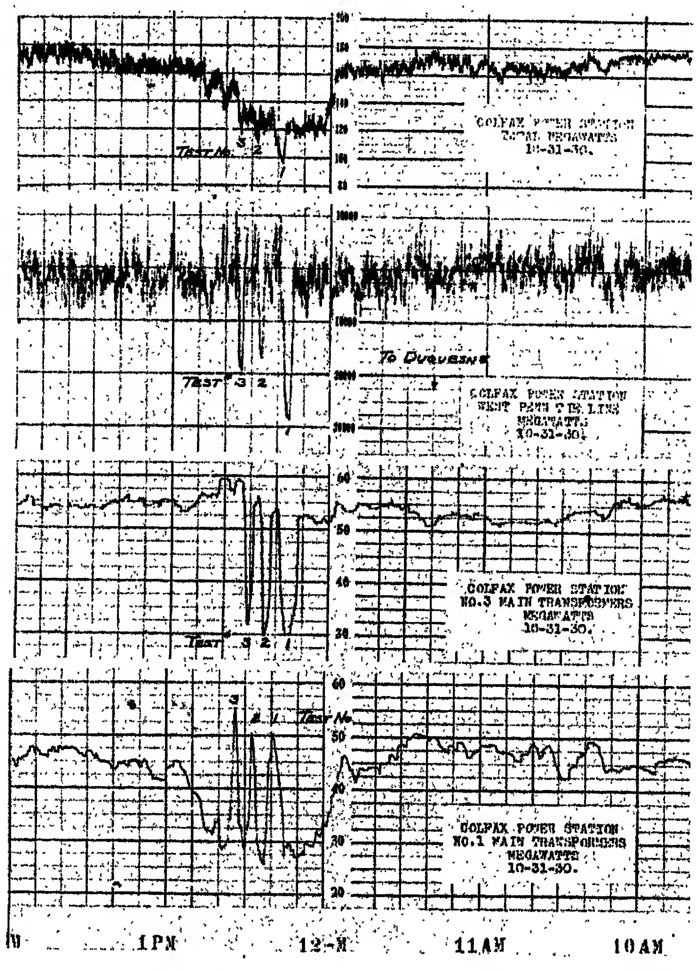

FIG. 12—INSTRUMENT CHARTS AT COLFAX DURING TESTS

load chart illustrating this effect. The erratic power swings are due to the fact that when there is a load change on one system there is a speed change which affects the governors on both systems. While the West Penn frequency regulator is attempting to readjust frequency, power flows over the tie line and the tie-line regulator functions to change the Colfax governor-speed settings until it is again in balance. The two regulators will continue to operate until a new steady state has been reached and the load change has been taken care of by the system on which it occurred. It is felt that while the solution to tie-line load swings may be temporarily put off by allowing frequency to drift, eventually system speeds will have to be held rigidly at 60 cycles and load

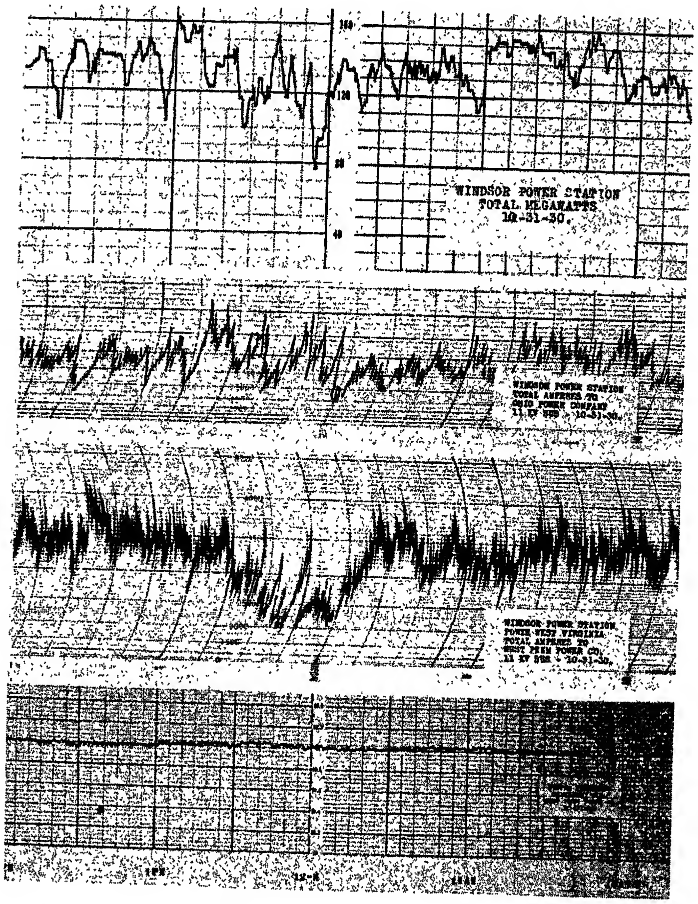

Fig. 13—Instrument Charts at Windsor During Tests

control on all tie lines utilized to permit maximum utilization of existing transmission facilities between the interconnected systems.

Another interesting observation has been the effect on the normal band of power swings with and without tie-line control. Fig. 10 shows that under manual tie-line load control the average load drifts without any appreciable change in the width of the band of power swings, whereas with automatic tie-line load control the average load is maintained very close to the desired amount, but the band of power swings is greatly enlarged. Fig. 11 is representative of the automatic tie-line control performance during periods of very light load, such as Sundays and holidays. The control gives a very narrow band and maintains the loading without any marked divergence from the normal load. This can be attributed entirely to the reduction in connected capacity and lack of fluctuating loads from industrial plants. During the period in which these charts were recorded the interconnected systems were under automatic-frequency control from the Windsor Power Station of the West Penn Power Co.

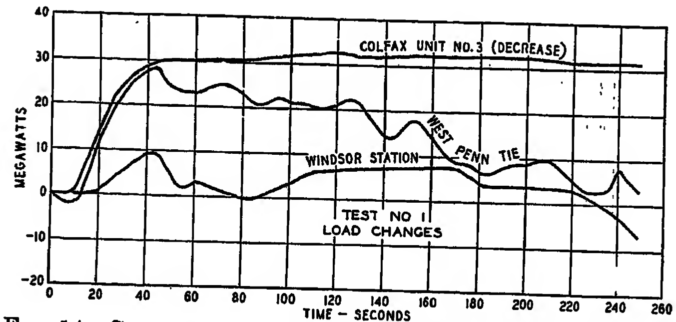

Fig. 14—Curves Showing Load Changes During Test No. 1

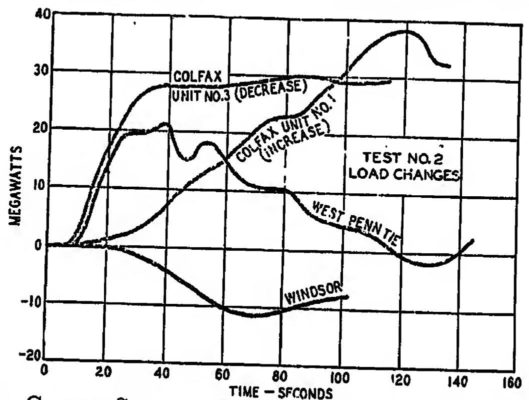

Fig. 15—Curves Showing Load Changes During Test No. 2

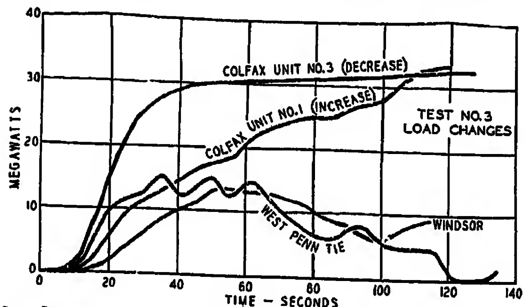

Fig. 16—Curves Showing Load Changes During Test No. 3

Tests were conducted by the Duquesne Light and West Penn Power Companies in October 1930, to determine the rate of response of the tie-line control and the frequency control to rapid load changes. This was accomplished by rapidly lowering the load on the Colfax Power Station 30,000 kw. and allowing the load and frequency controllers located at the Colfax and Windsor Power Stations respectively, to correct the load distribution and frequency without manual assistance. Figs. 12 and 13 show the records obtained on the station graphic instruments at Colfax and

Windsor during three consecutive tests. These are of interest primarily because of their time scale and because they are typical of those obtained in ordinary practise. For the purpose of analyzing the instantaneous load shifts, higher speed-test meters were used, and the results are shown in Figs. 14, 15, and 16. It will be noted that in all three tests, when 30,000 kw. was dropped on unit No. 3 at Colfax the power flow over the tie line increased almost simultaneously and at the same rate as the load was dropped. This initial division is a characteristic of interconnected systems when the load change occurs at the end of the tie line opposite from the point of frequency control. Without tie-line control the Windsor Station being under frequency control would have picked up the entire 30,000 kw. dropped. However, the curves show that in all cases the tie-line load control had accomplished considerable correction by operating on Colfax unit No. 1 before the frequency regulator at Windsor had caused that station to acquire much of the load dropped. All three tests were similar except that the speed of response of the tie-line load regulator was increased in tests No. 2 and No. 3. It will be noted that in the second test (Fig. 15) the load was dropped at Colfax generating station but was not picked up at Windsor, due to this station dropping load faster to compensate for load changes on its own system. This is shown on the Windsor charts of Fig. 12, and incidentally is a very good example illustrating the advantages of load diversity through interconnection.

Conclusions

1. It has been demonstrated that tie-line load regulators and program loading equipment have been developed to a commercial stage.
2. Tie-line load regulators on one system can be operated satisfactorily in conjunction with frequency regulators on a connected system.
3. It has been demonstrated that tie-line control may be used to reduce load fluctuations between interconnected systems.

Discussion

H. S. Fitch: Any discussion of this initial and timely paper on automatic tie-line control should consider first the nature of the interconnection, for upon the type of interconnection depends largely whether the operating problem is the proper loading of tie-lines or the stabilization of frequency or both. As the authors have stated, the important problem of this interconnection is that of controlling the interchange of power between the several systems.

The Pennsylvania-Ohio-West Virginia interconnection is a fairly compact one within an approximate total area of 101,000 square miles and is strongly interconnected by means of the 132-kv. transmission backbone throughout its principal component systems. The total normal running generating capacity is 4,000,000 kw., the Duquesne Light Company generating capacity is 360,000 kw. or approximately 10 per cent and the 132-kv. tie-line between the Duquesne Light Co. and the West Penn Power Co. is limited by transformer and regulator capacities or 36,000 kva. or to approximately 1 per cent of the total interconnected capacity.

Regulation of the load among the interconnected systems of this group and among the individual power stations of each system has been a most difficult problem. As each system joined the interconnected group it would have to scrap, in many instances, much of the operating practise of load and frequency regulation it had built up over a long period of operation. It was recognized early in the history of this interconnected system that in the problems of plant loading, tie-line control and complying with the terms of the many contracts by which each system interconnected with its neighbors, frequency control was a matter of vital consequence. Those companies which were interconnected with more than one other company at different points, were greatly limited in their ability to maintain correct loading on the various interconnecting tie-lines. While it was not difficult for a company on the side adjacent to the major frequency controlling station to maintain its tie-line load at desired value, it was difficult for those companies interconnected to it and farther away from the center of frequency control to regulate the amount of power flowing in its interconnecting tie-line.

The frequency of the system was constantly being changed by the various power stations attempting to regulate the flow on the tie-lines by opening or closing the turbine governors, especially during the abrupt load changing periods and it was usually 9 a.m. before the system settled down to the morning load, which steady condition would last until 11:45 a.m. The Working Committee of operating executives believed that if the frequency could be held at 60 cycles with but a very slight deviation —less than 1/20 of a cycle—the outlying company would need only to adjust its interconnecting tie-line load, the next company in turn adjust its tie-line load and so on to the last tie-line connecting to the central frequency regulating station. In this manner, the tie-line load equilibrium would not be disturbed.

Tie-line control on this interconnection was, therefore, first attacked from the point of view of frequency control for it was believed then, as the authors of this paper verify now—"that while the solution to tie-line load swings may be temporarily put off by allowing frequency to drift, eventually system speeds will have to be held rigidly at 60 cycles and load control on all tie-lines utilized to permit maximum utilization of the existing transmission facilities between the interconnected systems." It was exactly this problem that the operating engineers tackled in the early part of 1929 by assigning to Windsor Station the task of holding a flat frequency with six 30,000-kva. generators with one operator on each shift assigned practically the sole duty of holding a steady frequency by manual adjustment of the six governors. At that time no commercial type of automatic frequency control was available. The Windsor operators were to be more watchful over frequency, and more agile in adjusting it than the other operators of the system had been and were to concentrate on loading the station but maintaining a close frequency range, whereas all other operators were to concentrate on maintaining a close tie-line load adjustment manually and forget the frequency.

This new scheme of operation worked successfully from the start. Troubles with tie-line regulation seemed to disappear like magic. Whereas it had been usual practise to adjust tie-lines three or four times an hour, now three or four times a morning or afternoon or evening suffices.

The control of close frequency has not been a simple problem as stated by the authors, but has been one in which the manufacturers of the equipment have been actively engaged since 1929 and on which the Working Committee has applied much attention and made many tests gradually working toward a more rigid 60-cycle control. Three times equipment has been installed at Windsor by one manufacturer until now a very close frequency range is attainable and another manufacturer is now installing his equipment for test purposes.

At this writing, frequency control is installed not only at Windsor Station, but at Philo Station of the American Gas &

Electric Company and the Springdale Station of the West Penn Power Company to relieve the Windsor station of the large shifts in load at the load changing periods which were often as high as 80,000 or 90,000 kw. in 8 or 10 minutes. These three power stations by their firm interconnection may be considered to be the nucleus of the system and present a very compact and unified system of frequency control. So far no trouble other than adjustment of speed and amount of response has been necessary to keep these three frequency regulating devices in synchronism. The three of them in unison are doing a very satisfactory job. There has been no serious wear on the governor mechanism at any station due to speed change impulses of nearly 30 times a minute. The dispatching work of putting the control devices in and out of service and of regulating the number of generating units on each device at the three stations is supervised by the Windsor load dispatcher.

The control of frequency has been noticeably assisted by the automatic tie-line control installed on the Duquesne Light Co. interconnection which method is far superior to the manual method formerly used. However, it is very doubtful if automatic tie-line control would be effective with manual frequency control, especially with the kind of frequency illustrated in Fig. 1. Therefore, it appears that a rigid frequency control is the first essential, and it was after this advantage had been secured that tie-line control was installed by the Duquesne Light Co.

Too great emphasis cannot be laid on the statements made by the authors in column 1, page 41 in regard to the use of automatic control to secure the maximum economy possible as a result of the interconnection and to obtain the most efficient loadings of the several generating units. Especially true are the statements that the regulator must not respond to transient load change, but it must respond to small sustained changes. The uses to which the program load controller can be put to obtain these maximum economies will be quickly recognized by every operator. Most operators and several load control devices do not sufficiently take into account the inefficiency due to operating with steam control valves in a throttling position; neither do they allow the economies of very careful operation by having the turbine valve steadily wide open without cracking the next valve. Very close frequency control is necessary for this work.

The tests made by the authors have advanced the subject immeasurably, and they have indicated new methods to operate interconnections more successfully and with greater economy. The job of operating smoothly one large interconnected area with another over a comparatively weak tie-line, each area having a multitude of interconnections, is now providing problems every day for the operating executives of the Chicago, Southern and Pennsylvania-Ohio groups. Whether the answer lies through frequency control or tie-line control, or more probably through the correct application of both methods, is one now sought by tests being continually made by the operators of these systems and the manufacturers of these devices.

Philip Sporn: This paper deals with a problem that is of utmost importance in the operation of interconnected systems' and a problem that is at present receiving a very considerable amount of study. Experience is gradually being obtained with automatic control, and I believe that the final answer depends upon the proper application of automatic control, but not necessarily and certainly not primarily by automatic tie-line control.

In discussing the interconnection problem, the authors refer to operation of the Chicago, Boston and New Orleans systems in parallel when occasion arises for exchange of power. At present there is no economic justification for parallel operation of the various areas mentioned and if they do finally operate in parallel, there will be nothing planned about such operation, but rather, it will be accidental. Power exchange will be a process of relaying and not any actual exchange of power, for example, from Chicago to Boston.

The statement is made that any attempt to regulate two or more interconnected systems with automatic frequency control on each will develop the fact that load variation on the two systems will be so dissimilar that regardless of frequency control, the power flow over tie lines cannot be regulated. This has certainly not been the general experience to date. Experience has shown that automatic frequency control on each of two systems operating in parallel greatly reduces the fluctuation on the tie line, and in one instance was the only practical means of operating the systems in parallel through a relatively weak tie line.

I certainly believe that automatic tie-line control has its place in the operation of interconnected systems and the authors are to be congratulated for the work they have done along the development of such apparatus. However, I do not at all agree with them that the matter of frequency control is comparatively simple and that the entire question practically resolves itself into one of tie-line control.

In my opinion the authors have attacked this problem from the standpoint of a very special case that could hardly be classed as a typical interconnected network since the tie line is of relatively low capacity and further, that there is only *one* tie line between the systems. The case cited in this paper is one in which two areas with generating capacities with a ratio of about 10 to 1 are connected together through a *single* tie (transformer in series) of relatively small capacity. The question is considerably more complicated with two or more large systems connected together through numerous tie lines. In the latter case, it appears from a great deal of work that we have done on the problem to date, that distributed frequency control is the proper solution if we are to keep away from expensive phase shifting equipment in tie lines.

The paper describes tests that were made by the Duquesne Light Company to demonstrate the action of the tie-line controller when generating capacity was dropped on the Duquesne Light Company's system and showed in every case that Windsor, the frequency controlling station, picked up considerable of the load before the tie-line controller was able to make the proper correction. This definitely brings out the fact that the frequency controlling station must always take a certain amount of the "fringe." An interconnecting system in which only one station is designated to hold frequency and in which all other sections have automatic tie-line control will result in the frequency controlling station taking the accumulated fringe of all parts of the systems. On an interconnection of any size, this will amount to considerable capacity, perhaps at times in the order of 100,000 kva. and this would most certainly impose an undue burden on the frequency regulating station. The result is that the system having the station under automatic frequency control must "hold the bag;" this might perhaps be a satisfactory way of doing the job if it were possible to get someone to agree to take the power swings due to frequency regulation. In the ultimate set-up, I do not believe anyone will be willing to sacrifice station economy in order to hold very close frequency, so that each of the interconnected companies may work out its own ideal economy or contract loading program.

Interconnection has been a process of tying together systems that had normally been holding their own frequency, and when these companies started operating in parallel, it was natural that each should attempt to continue to hold frequency. The main difficulty with this method of operation was that the frequency recorders did not have the same degree of accuracy, and naturally resulted in each system attempting to hold a slightly different frequency. Such a condition usually resulted in tie-line loading difficulties.

These difficulties led to the next step which was to designate one station to hold frequency and for other interconnected companies to follow their own loads very closely, so as not to upset tie-line loading. At first the designated station held frequency manually and the improvement over the old method of operation was so marked that automatic frequency control was installed in the one station. While the operation was very much improved over the old method of each station watching frequency,

there was nevertheless considerable burden placed on the regulating station. This was mainly due to the fact that manual control on other parts of the system was slow as compared to the automatic control.

This led to the conclusion that for a complicated interconnected system, distributed automatic frequency control would be the ultimate solution. It was realized that this was not a simple problem and that it should not be inferred that the problem has been entirely solved by installing an automatic frequency controller in one station of each of the interconnected companies. The installation of a frequency controller in a given area may smooth out regulation over the interconnecting tie line, but at the same time may create regulation difficulties within the system on which it is installed. The final solution of this difficulty may be additional frequency controllers within the given area, and it is in such cases as this that the automatic tie-line controller may be the ideal solution. But, the fundamental problem will still be one of frequency control. Undoubtedly there will be cases where some limit must be set up as to the amount of power that can flow on tie lines, but the tie-line control should ordinarily be a supplement to frequency control. As a matter of fact, tie-line control itself, such as described by the authors, approaches the question from the standpoint of frequency, because any attempt to adjust governors on one system so that it will supply its own load demands and limit the incoming or outgoing on a tie-line to another system, aims in effect to keep the speed constant.

Experience has borne out the belief that automatic frequency controllers at several stations operate satisfactorily in parallel. For some time the Windsor plant has been holding frequency for a large interconnected system. Undue burden has been placed on this station and relief was sought by installing additional frequency control at other stations. A series of tests in conjunction with two manufacturers is now in progress with frequency control at the Philo plant of The Ohio Power Company, at the Springdale plant of the West Penn Power Company, and at the Windsor plant, which is jointly owned by the West Penn Power Company and The Ohio Power Company. To date operation has demonstrated that available frequency controllers operate satisfactorily in parallel and that they have greatly reduced the swings on Windsor plant. It is of course necessary for system operators to become familiar with automatic frequency control if the results are to be satisfactory. In some cases it may be necessary for them to change their ideas somewhat as to the accustomed methods of operation. One fact that has already been demonstrated is the possibility of having too much capacity under automatic control for a given system load. However, this does not mean that there are too many points of control. It is felt that the surface is only scratched and that the ultimate solution depends on proper distribution and coordination for parallel operation of these automatic controllers.

One of the most important justifications for interconnection is the mutual help that it renders possible during emergency conditions. As at present applied. automatic tie-line control is not entirely satisfactory from this standpoint, that is, if there is a need for help on the system which has automatic tie-line control, this controller will allow power to come in from the interconnection. However, if need for help arises on the other end of the interconnection, the controller will attempt to limit this power flow. Undoubtedly a proper solution of this difficulty can be worked out, but this will probably mean cutting out the tie-line control during such cases of need. On the other hand, if there is frequency control on both sides of the tie line, the situation is somewhat different and it seems to me more satisfactory in that it will allow the maximum amount of help during emergency conditions. There are of course cases where the amount of power that can safely be exchanged between two systems is fixed by line and transformer limitations. In such cases, it may be necessary to use tie-line control.

As stated previously, I believe this problem of operation of interconnecting systems must be attacked from a very broad standpoint and worked out in such a way that all concerned will obtain the maximum benefits to be derived from such interconnections. A solution which imposes undue burden on any system, or acts as a check on the usefulness of interconnection facilities, will ultimately fall down.

John Gosinski: The operation of the tie-line load regulators described in this paper is concerned mainly with normal operation of a tie line, that is, for the transmission of a predetermined amount of power. It will be found that interconnections between neighboring systems are relied upon not only for a normal transfer of power but also for a definite portion of system reserve capacity for use during major system transmission line or generator outages.

Since the value of an interconnecting tie line proves itself by its ability to swing in for large blocks of power in an emergency, any regulating device should preserve this feature of an interconnection. It would be desirable to have the regulating device differentiate between the normal load drifts between systems and a sudden abnormal demand caused by loss of capacity by the neighboring system so that for the latter condition the tie-line regulator would become inoperative.

Quite frequently a generating plant for load regulation may be a considerable distance away from the tie-line terminal, so that the impulses from the tie-line regulator would have to be transmitted over distances as great as 100 miles. The impulses of the regulator should, therefore, have such characteristics as to be suitable for transmission over the less expensive type of telephone or telegraph transmission channels.

R. Brandt: This paper brings forcibly to the front the fact that the main problem to be faced in growing interconnections is that of making the power flow in predetermined amounts and predetermined directions. Frequency control as an end in itself is desirable only from the relatively minor point of view of synchronous clock time. As a step in the solution of the major operating problem, it is, however, of extreme importance since it furnishes a firm, steady foundation without which it would be futile to try to control tie-line loadings.

For two reasons then the development of frequency control has been pushed in the New England region; (1), because it was the logical first step in the general solution of the interconnection problem, and (2), because it could be accomplished fairly readily as the authors of the paper point out, and that its accomplishment did carry with it some desirable results. It can even be rather definitely stated that frequency control has had a steadying effect on tie lines and has, therefore, accomplished at least partially the solution of the main problem.

There are undoubtedly some cases where tie-line control will serve the purpose better than speed control, and the case cited in the paper appears to be one in point. It must not be lost sight of, however, that unless speed were being held steady somewhere else the excellent results obtained with the equipment described would hardly have been found. The case of the Duquesne Light Company when connected with the West Penn Power Company, and through them to an extensive interconnection network by means of one short, strong tie terminating directly at a power station was an almost ideal location for tie-line control, and full advantage has been taken of this fact. Its extended application, however, to the more general case of a system which may be interconnected at the same time with two, three or more adjacent systems over relatively long ties, geographically separated by a hundred or more miles, and terminating at high tension substations rather than controllable sources of power, so complicates the situation as to make the application of any such tie-line controls as are at present available quite impractical.

Frequency control on the other hand does offer at least some measure of help in the complicated general case. Automatic

equipment in operation on adjacent systems will have a steadying effect in all of the tie lines between the systems so equipped.

All this does not mean that swings will be eliminated. They may even increase in number, but their average magnitude should be reduced. During the steady load periods of the day it is probable that the ups and downs of the fringe of the load curve on adjacent systems will not absolutely coincide, and that some unnecessary transfer may be brought about which will have to be later corrected. However, any transfer from this cause is minor compared with that which occurs during the fast changing periods of the morning, noon and late afternoon. At these times, the direction of load change on all interconnected systems which do not cross time belts will most certainly be in the same direction and at the same time. In this case the simultaneous operation of frequency controllers having substantially the same sensitivity and response characteristics is of undoubted benefit.

The mechanical devices described in the paper have been well thought out and have served their purpose admirably. In particular, the anti-hunting feature which takes into account the momentum which has to be established and later destroyed in bringing the system from one load condition to another is well explained.

The authors are to be congratulated on the soundness of the conclusions reached, based on the conditions covered by their experience, and on the useful definitions of the requirements of successful tie-line load control.

L. F. Hunt and M. MacFerran: The paper is of especial value in pointing out that the problem of frequency control is intimately related to that of load control, *i. e.*, the division of load among machines according to some predetermined schedule. It is important to note that the desirability of properly correlating load and frequency control is not confined to independent systems connected by a light tie line, but extends also to any system which has several sources of energy which must be coordinated. Especially is this true when two or more units are necessary for regulation.

The use of the hydraulic speed changer is a very interesting development. The question suggests itself as to whether this device does not introduce one more time-consuming step into the already complicated chain of events involved in the action of the governor and the compensating or speed-changer spring. In fact, the very circumstance that makes the hydraulic attachment necessary—the operation of the speed-changer spring 30 times a minute—suggests that the whole governor mechanism is now being put to a use for which it was never intended. Originally the governor and compensating spring were designed to give a drooping speed-load characteristic suitable to the operation in parallel of numerous governed units. Then the necessity for constant frequency gradually arose, and the burden of the regulation was all placed on one unit or plant, with an auxiliary frequency-control device acting constantly to change the tension of the compensating spring. The net result is a perfectly flat speed-load characteristic, obtained not by direct and simple means but by a long chain of adjustments and readjustments. This complicated mechanism, while functioning fairly well under normal load conditions, is unduly sluggish and unresponsive during transient conditions, because there are so many points of slack and lost motion. It would seem that modern conditions dictate a more direct method of control, as for instance an electric frequency device working directly on the pilot-valve of the machine. Such a scheme can readily be extended to include automatic load division control when two or more machines do the regulating.

P. B. Juhnke: This presentation corroborates effectively the opinion held by the writer for some time to the effect that tie-line regulation apart from frequency of regulation is an essential part of system regulation. No matter how fine the regulation and control of frequency may be, drift of power over interconnected ties cannot be entirely avoided without special attention and effort. With frequency of regulation neglected, these drifts will easily reach the limits of the tie-line relay settings and consequently cause trip-outs of interconnecting elements.

This tie-line regulation may be accomplished in different ways. It may be through phase shifting or through action on turbine governors, actuated in either case by the tie-line load. But it must be present and of ample dimensions to accomplish its purpose. Then frequency of regulation can best accomplish its object and the result is a system greatly stabilized and able to function as desired.

T. E. Purcell and C. A. Powel: Most of the experience cited confirms that of the authors but the conclusions drawn are not always identical.

Mr. Fitch has given an excellent summary of the operating experience in his district. It might be interesting to note that the increasing power exchanges between the West Penn system and the Duquesne Light system after automatic frequency control was adopted on the West Penn system led to the installation of automatic tie-line load control on the Duquesne-West Penn interconnection in order to prevent the load changes on the Duquesne system from being transmitted over the tie-line. Experiments had previously been made with automatic frequency control on the two systems but it was found that the tie-line load could not be held within the required limits by this means. Experience since the presentation of the paper indicates that the performance of the tie-line control is not influenced by the quality of the frequency regulation on the interconnected systems. Tie-line control does have a stabilizing effect on the frequency of the interconnection.

Mr. Brandt has given an excellent contribution of his experience in the New England area. It would be interesting to be able to compare an installation of tie-line load control and parallel frequency control on the long tie lines of his system with the results obtained on the Duquesne-West Penn tie. Messrs. Brandt and Gosinski point out that in many cases the tie-line to be controlled is remote from any generating station. Two of the tie-line load regulators shown in Figs. 3 and 4 of the paper are so designed that they can be adapted to remote control.

The use of frequency regulators to accomplish phase-angle control, as referred to by Mr. Sporn, would undoubtedly lead to undesirable distribution of load between generating stations, thereby resulting in decreased efficiency of generation. It is the authors' opinion that this loss might be great enough to more than justify the installation of phase-angle control equipment.

It seems to the authors that the conclusions drawn by Mr. Sporn from the experience at Windsor during the test described in the paper are not fully justified. No doubt the frequency controlling station may take a certain amount of the fringe but the tie-line load regulator is much more sensitive on a large interconnection than any automatic frequency control can be. It seems to the authors that Mr. Sporn has presented a very excellent argument for automatic tie-line control as he points out in his discussion that frequency control in one station is desirable, but up to the present time has not been successful on his system due to the difficulty under such condition of holding load on tie lines within proper limits. This can be accomplished most ideally by the use of the automatic tie-line load control equipment described in the paper. The automatic tie-line control regulator can be so biased with frequency that it can be made to function in the desired manner during emergencies.

With regard to the questions raised on the use of the hydraulic speed changer, we have found the introduction of a program load control eliminates excessive wear on governor parts of any individual machine. The question raised by Mr. Hunt and Miss MacFerran is well taken. Perhaps there are other or better ways of controlling the speed than by the use of the hydraulic speed changer. However, this mechanism not only allows the governor to function well under normal conditions, but also under transient conditions. Full load may be suddenly dropped from this machine without excessive increase in speed.

Tuned Power Lines

BY H. H. SKILLING*

Associate A. I. E. E.

Synopsis.—A new approach to an important problem in the ld of electric power is offered by the author, who limits his dis- ssion to the possibilities of tuned lines rather than their practical 'plication. He presents the results of extensive research work, and on the basis of laboratory experiments points out that through the use of higher transmission frequencies, the efficiency of a given line might be increased as much as 500 per cent.

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ESS than 50 years ago when electrical engi- neering was young, there was vital and active interest in subjects which today are taken erally for granted. In early electric power work t the least of these was the question of choosing a sirable frequency for a-c. systems; 20 cycles, or 50, 100? It was only natural that discussion pertaining the frequency question considered principally the lative merits of different frequencies from the point view of electric machinery—generators, motors, and ansformers—with practically nothing said of the en simple subject of electric power transmission.

Thus it is that the large electric power networks of lay find themselves definitely committed to certain quencies earlier chosen for various expedient reasons. ow there is a definite trend toward the use of more d longer transmission lines for carrying large blocks power from generation centers to load centers. In s connection the question of transmission stability supreme; hence it is considered justifiable to reopen question of desirable frequency, and to study it m the long lines point of view. It is well known of urse that transmission characteristics of a given stem may be improved by the use of frequencies ver than those now in vogue; but no general study of influence of frequency has been published.

While the fundamental transmission line equations :

$$E_g = E_r \cosh \sqrt{Z\,Y}\,l + I_r \sqrt{\frac{Z}{Y}} \sinh \sqrt{Z\,Y}\,l$$

$$I_g = I_r \cosh \sqrt{Z\,Y}\,l + E_r \sqrt{\frac{Y}{Z}} \sinh \sqrt{Z\,Y}\,l$$

ere

- E is voltage
- I is current
- g subscript, signifies generator end of line
- r subscript, signifies receiving end of line
- Z is impedance per unit length of line
- Y is admittance per unit length of line
- l is length of line

it is most convenient to discuss transmission operation in terms of the general circuit constants:

$$A_o = \cosh \sqrt{Z\,Y}\,l^*$$

$$B_o = \sqrt{\frac{Z}{Y}} \sinh \sqrt{Z\,Y}\,l$$

$$D_o = \cosh \sqrt{Z\,Y}\,l$$

$$C_o = \sqrt{\frac{Y}{Z}} \sinh \sqrt{Z\,Y}\,l.$$

For ordinary transmission lines and for frequencies higher than about 10 cycles per sec., the value of factor $\sqrt{Z/Y}$ is practically constant and need not be considered as a function of frequency in this discussion. Hence the general circuit constants are proportional to the hyperbolic functions. However, if the resistance of the line in question is low compared with the reactance, and if the leakage from line to line is small, factor $\sqrt{Z\,Y}\,l$ becomes purely imaginary and

$$A_o = \cos \sqrt{\mathbf{Z\,Y}}\,l^*$$

$$B_o = j\,Z_o \sin \sqrt{\mathbf{Z\,Y}}\,l$$

$$D_o = \cos \sqrt{\mathbf{Z\,Y}}\,l$$

$$C_o = j\,\frac{1}{Z_o} \sin \sqrt{\mathbf{Z\,Y}}\,l$$

with $Z_o = \sqrt{Z/Y}$, the characteristic impedance of the line.

Thus it is made evident why low frequency gives good transmission characteristics. The desirable conditions are low voltage regulation under load, small charging current when lines are unloaded, and high synchronous stability. All three of these factors require a low value for B_o while synchronous stability requires also a value of A_o approximately unity. Both of these conditions are obtainable with low frequency because Z and Y both are proportional to frequency, and as they decrease in value, the sine of $\sqrt{\mathbf{Z\,Y}}\,l$ decreases while the cosine of the same angle approaches unity.

Conversely undesirable transmission characteristics are encountered when the value of $\sqrt{\mathbf{Z\,Y}}\,l$ approaches $\pi/2$, because then the cosine approaches zero while the

Stanford University, California.

resented at the Pacific Coast Convention of the A. I. E. E., e Tahoe, California, August 25-28, 1931.

*Bold-face symbols (**Z**, **Y**) indicate absolute values (magnitude only) time relationships as indicated by angles omitted.

sine is near unity. Operation under such conditions is impractical because (1) regulation is so poor that with constant generator voltage the load is required to take practically constant current, (2) line charging current increases *indefinitely* as the receiving voltage rises, and (3) synchronous stability is possible only at extremely low power factor.

If the value of $\sqrt{\mathbf{Z}\,\mathbf{Y}}\,l$ lies between $\pi/2$ and π, synchronous loading is quite impossible, but a static load may receive power. The static power limit (which is determined by voltage regulation and occurs at the load for which $d\,P_r/d\,E_r = 0$) becomes very large as $\sqrt{\mathbf{Z}\,\mathbf{Y}}\,l$ approaches π, because $\sin \pi = 0$. For the same reason charging current to the line is very small; hence, transmission conditions are as good when the frequency makes $\sqrt{\mathbf{Z}\mathbf{Y}}\,l = \pi$ as when the frequency is very low, except for the possible lack of synchronous stability.

An important point worthy of detailed consideration is that where the frequency used makes the value of $\sqrt{\mathbf{Z}\,\mathbf{Y}}\,l$ slightly greater than π, and synchronous stability also is attained. The terminal steady-state conditions are identical when $\sqrt{\mathbf{Z}\,\mathbf{Y}}\,l = k$ and when $\sqrt{\mathbf{Z}\,\mathbf{Y}}\,l = k + n\,\pi$ with k representing any value of the function and n any integer. The truth of this statement for the idealized case under consideration is evident from the fundamental transmission line equations. The physical meaning is that transmission is good over a line the length of which is equal to a very small fraction of a wavelength of the transmitted voltage, and that it is equally good over a line the length of which is equal to a half wavelength or any multiple thereof. But this consideration includes only steady-state terminal conditions of a line without losses; certain modification is necessary before this statement may be considered to apply generally.

When line losses from resistance and leakage are not negligible it is best to use the hyperbolic-function form of general circuit constants. No change in the general understanding of conditions need occur, but the definiteness of the ideal line is lost; the power limit now is not infinite (as when $\sqrt{Z\,Y}\,l = j\,\pi$) nor is synchronous stability either absolutely perfect or absolutely impossible. No longer is it quite true to say that $j\,\pi$ may be added to $\sqrt{Z\,Y}\,l$ without changing terminal conditions. These things are nearly true, but not quite.

However, a point of far greater importance than line losses is the effect of terminal machinery. Even in the simplest system the general circuit constants will be modified by the generator, the transformers, and the load. If the apparatus at the sending end introduces a series impedance Z_1, and the receiving end apparatus introduces a series impedance Z_2, the general circuit constants become:

$$A_o = \sqrt{\cosh}\,\sqrt{Z\,Y}\,l + \frac{Z_1}{Z_o}\sinh\sqrt{Z\,Y}\,l$$

$$B_o = Z_o \sinh\sqrt{Z\,Y}\,l + (Z_1 + Z_2)\cosh\sqrt{Z\,Y}\,l + \frac{Z_1\,Z_2}{Z_o}\sinh\sqrt{Z\,Y}\,l$$

$$C_o = \frac{1}{Z_o}\sinh\sqrt{Z\,Y}\,l$$

$$D_o = \cosh\sqrt{Z\,Y}\,l + \frac{Z_2}{Z_o}\sinh\sqrt{Z\,Y}\,l.$$

But if the line is long and the machinery is designed to have fairly low synchronous reactance, the only change in the constants that need be contemplated here is that a term must be added to B_o:

$$B_o = Z_o \sinh\sqrt{Z\,Y}\,l + Z'\cosh\sqrt{Z\,Y}\,l$$

where Z' is the total impedance of the machinery. This is an approximation, but it is almost true when the value of $\sqrt{Z\,Y}\,l$ closely approximates π or is any multiple of π. It is not at all applicable if the value of $\sqrt{Z\,Y}\,l$ approximates $\pi/2$, but it may be generally used because it applies whenever transmission characteristics are favorable.

Transient synchronous stability usually is investigated only after line and armature transients have died out; therefore as in the case of steady-state stability, only terminal line conditions are effective. A half-wavelength line would have the same order of transient stability as a low-frequency line except as the terminal machinery might be altered.

Traveling Waves

The nicest description of the operation of a line is in terms of traveling waves. The generator may be considered as imposing on the line a series of electromagnetic waves which travel on the line to be more or less reflected from the receiving end, setting up a wave train traveling back toward the generator. Where the line is short a reflected wave returns to the generator so quickly after its initiation that it still is very closely in phase with the wave leaving the generator. Under this condition the voltages and currents of the two wave trains will add algebraically at the load end (assuming the load impedance to have the same angle as the characteristic impedance of the line) and differ by only a small angle at the generator end. Therefore, if attenuation is low the load voltage will be almost equal to, and in phase with, the generator voltage.

If the line be longer there will be a correspondingly larger difference in phase relation at the generator between the outbound and the returning wave. This involves trigonometric addition of effective voltages and currents at the generator and even with low attenuation, line regulation may be bad. However, if the line be of the proper length the reflected wave will arrive back at the generator just one cycle after its initiation there and consequently in phase with the next wave leaving the generator. Voltages and currents again will add algebraically and line regulation

will be very good because the reflected wave will increase both end voltages equally. In this case as with the very short lines the load voltage will closely approximate the generator voltage (if attenuation is low) but 180 deg. out of phase.

The last few paragraphs have spoken of "long" and "short" lines. This refers to the electrical length of the line considering wavelengths rather than miles. However, a half-wavelength line is one for which the imaginary part of $\sqrt{Z\,Y}\,l$ is $j\,\pi$, and hence it may be either a short line operating at high frequency or a very long line operating at normal frequency. Representative dimensions of a half-wavelength line are: 200 mi. long and 450 cycles, or 1,400 mi. long and 60 cycles.

The fact that apparatus at the ends of a line introduces impedance that increases the electrical length of the line already has been mentioned. It was shown that, approximately,

$$B_o = Z_o \sinh \sqrt{Z\,Y}\,l + Z' \cosh \sqrt{Z\,Y}\,l.$$

Since good transmission conditions demand that $B_o = 0$, it is desirable that

$$\sinh \sqrt{Z\,Y}\,l = -\frac{Z'}{Z_o} \cosh \sqrt{Z\,Y}\,l.$$

The hyperbolic cosine may be considered to be unity, either positive or negative. The lowest value of $\sqrt{Z\,Y}\,l$ that approaches a solution of this equation will be between $\pi/2$ and π where the hyperbolic cosine will be negative and hence the values of frequency and length of line to be chosen should as nearly as possible make

$$\sinh \sqrt{Z\,Y}\,l = +\frac{Z'}{Z_o}.$$

Consequently when terminal apparatus is considered, a shorter line or a lower frequency should be used than those given as representative in the preceding paragraph. If it is desired further to shorten the line or lower the frequency, more inductance may be introduced into the line, preferably in combination with static condensers across the line; this will result really in a section of "artificial line."

The presence or absence of synchronous stability for any given line may best be found graphically. Such methods, based on the circle diagram of the transmission line, tell at once the whole story of load limit, stability, regulation, and other factors. Although many statements in this paper now appear somewhat obscure in the light of the equations only, they become perfectly clear when the circle diagrams are studied. The diagrams unfortunately are too voluminous to be included, but Fig. 1 shows results obtained from such charts for a 202-mi. 220-kv. line having three 500,000-cir. mil cables spaced 15 ft. apart in a vertical plane; terminal apparatus not included. Under these conditions the value of sinh $\sqrt{Z\,Y}\,l$ reaches a minimum at 447 cycles. Whether or not there might be synchronous stability at this frequency depends upon the synchronous machinery; it is probable that there would be. It may be seen that the maximum power per phase to be received at 60 cycles by a unity power-factor load is about 50,000 kw. Lagging power factors are much worse, and leading power factors are not much better. With transmission at 447 cycles the maximum power (if supplied to a static load or to an induction motor) obtainable is more than five times the 60-cycle limit.

The reason for the peculiar action of a half-wavelength line is essentially quite simple. The capacitance of the line is so balanced against the inductance

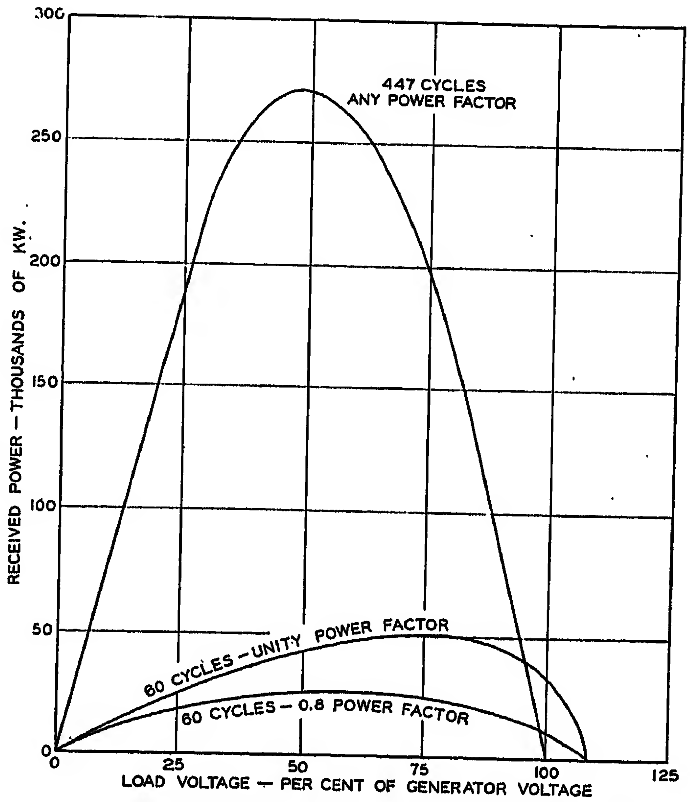

FIG. 1—POWER LIMITS OF AN OPERATING 202-MI. 220-KV. LINE FOR NORMAL 60-CYCLE OPERATION AND FOR SUGGESTED 447-CYCLE OPERATION

of the line that the undesirable effects of both disappear. On an exact half-wavelength line with no losses and without load, with voltage maintained by a generator, the voltage at the receiving end would be equal and opposite to the voltage at the generator; in the middle of the line the voltage would be zero. The momentary charge at any point of the line would be proportional to the voltage; hence charging current would not need to be supplied from the generator, but merely would flow back and forth from one end of the line to the other each half cycle. Although there would be no current flowing at either end of the line, there would be a large current at the middle where the voltage would be low.

If load impedance were equal to the characteristic impedance of the line, current and voltage both would be constant along the line, but retrogressing angularly through 180 deg. The charging current would be passed on by each differential section of line to its neighbor as the voltage wave travels, finally to be used by the load.

If load impedance were less than the characteristic impedance, the current would be least at the middle of the line where the voltage would be highest. This resonant voltage rise is valuable because it makes efficiency and regulation of such a line better than could be obtained even from d-c. transmission; by proper insulation, reactance of the terminal machinery, and proper choice of the characteristic impedance of the line, resonant voltage rise may be prevented from becoming troublesome.

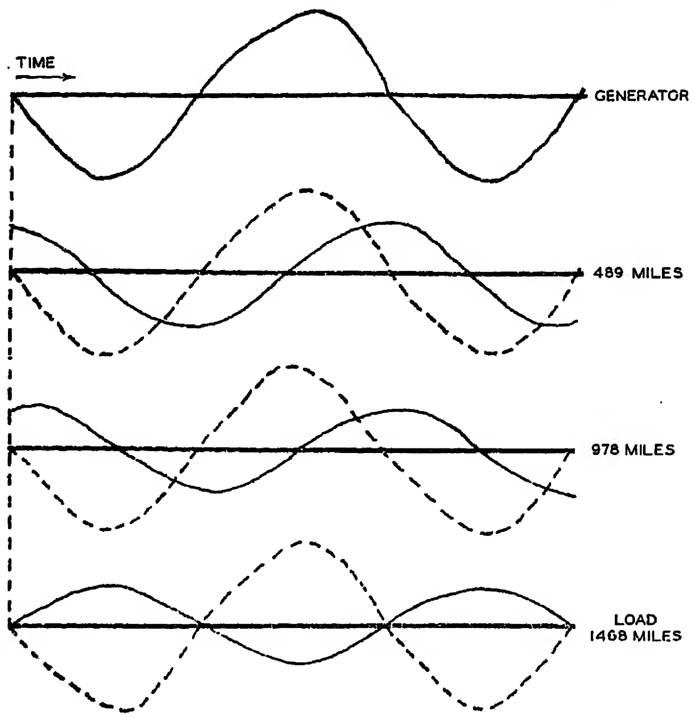

Fig. 2—Tracings from Oscillograms Showing Voltage Phase Relations Along a 1,468-Mi. Tuned Line as Compared with Generator Voltage (Dotted)

It is because of the interaction of the distributed inductance and capacitance that such a line is called a "tuned line." The similarity to a tuned radio circuit is striking.

As evidence that a tuned line will behave as predicted by the fundamental equations, power was transmitted at 60 cycles over a 1,468-mi. artificial line. The characteristics were those of the 220-kv. line previously described (which may be recognized as the Pit River line of the Pacific Gas and Electric Company, Calif.) and the potential used was 127 volts to ground, 0.001 of the real line voltage with a corresponding factor of 0.000001 for the power per phase as compared to the real line. The receiving end was arranged for loading with either a static impedance of any power-factor or with a single-phase synchronous motor. Extensive tests were made and the observed characteristics were found to be in close accord with the computed expectations; synchronous stability of the system was found to be exactly as expected. The half-wave-length line plus the reactance of the synchronous motor gave fair stability. The introduction of reactance into the motor leads was found to improve stability greatly, at the expense, however, of power limit. When the line was shortened to slightly less than a half-wave-length, it was impossible to keep the motor in synchronism; no synchronous power could be obtained although resistance loads continued to operate.

Fig. 2 shows reproductions of oscillographic records of voltages along the artificial line. Load impedance was somewhat less than the characteristic impedance of the line, and there was noticeable resonance. That the receiving voltage actually was lower than the sending voltage was due to the heavy load, the long line, and the unavoidable losses in the artificial line that do not properly represent a true line. Regulation would have been worse had the load been applied at an intermediate point.

While the subject of this paper considers the possibilities of the tuned line rather than its practical application and the details incident thereto, it seems quite reasonable to suggest that it is not at all impossible that 400-mi. transmission at 150 cycles will offer attractive economic possibilities. With the use of such a line of course motor-generator sets (probably induction machines) would be required for frequency-changing, but costly synchronous condensers would be eliminated. Even so considering the cost of building and maintaining 220-kv. lines it seems reasonable that even a relatively large amount of terminal equipment could be justified if it would eliminate one long line.

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3. *Power Limitations of Transmission Systems*, by R. D. Evans and H. K. Sels, A. I. E. E. Trans., Vol. XLIII, 1924, p. 26.

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Discussion

F. E. Terman: Some years ago I was in rather close contact with a group of engineers who were investigating the possibilities of a 500-mile 60-cycle transmission system. The chief difficulty encountered was in the low power limit of the transmission network at 60 cycles, and this ultimately proved the obstacle which prevented the project from materializing. In order to get around this difficulty many expedients were considered, such as raising the transmission line voltage to about 300 kv., lowering the frequency to 15 or 25 cycles, using intermediate synchronous

condensers, etc., but it never occurred to anyone that raising the frequency to perhaps 150 cycles might be the solution to the problem.

The question as to whether tuned power lines will ever be employed in practise is of course dependent upon the economics of the future, but they are unquestionably a possible means of transmitting large blocks of hydroelectric power to distant load centers, and their consideration certainly upsets a number of preconceived ideas that most of us have held.

A. A. Kroneberg: As stated by the author, the subject of this paper is not so much the practicability as the possibility of the tuned line. As such it is quite interesting.

There are several questions that may be asked:

1. In formula $B_o = Z_o \sinh \sqrt{ZY}\, l + Z' \cosh \sqrt{ZY}\, l$ on page 50 of the paper where Z' is the total impedance of the machinery. This value varies with the load, being large at light loads when considerable machinery is taken off the line and reaching a minimum when all the machinery of the system is in service. Does it not mean that the line would have to be operated at different frequencies to take care of variations in Z'? With the load decreasing Z' will be increasing, calling for a shorter line or a lower frequency. Thus the prime movers of the generating station will have to be provided with speed control and the whole system will be operating at a variable frequency. The author suggests that the line length could be controlled by introducing more inductance in series, preferably, with static condensers across the line. This, of course, would enable us to fix the frequency of the system. It would be of interest to know how this could be accomplished in actual operation.

2. A statement on page 52 is open to objection. "Transient synchronous stability usually is investigated only after line and armature transients have died out." The step-by-step, torque-angle, and voltage methods of studying transient stability do not wait for the line and armature transients to die out. After transients die out there is no "transient" stability problem; it becomes a steady state solution.

Edith Clarke: Mr. Skilling has pointed out that a line of wavelength slightly over one-half wave (terminal machine impedances included) has good operating characteristics and power may be transmitted with stability from a synchronous generator at one end to a synchronous motor at the other, while for the line slightly under one-half wavelength no synchronous power can be transmitted.

The same conclusion will be reached by comparing the angles of the general circuit constants A_o and B_o, for lines (plus terminal equipment) of different wavelengths.

With constant excitations on generator and motor, maximum power will be delivered to the motor when the angle between the internal voltages of generator and motor is equal to the impedance angle of the general circuit constant B_o. With E_r as reference vector the angle of E_g must not, therefore, exceed the angle of B_o for the machines to remain in synchronism under steady state.

From vector diagrams of the equation

$$E_g = E_r A_o + I_r B_o$$

it may be seen that when the angle of the constant A_o is smaller than that of the constant B_o the power factor at the receiving end may be lagging, unity, or leading; but when the angle of A_o is larger than the angle of B_o the receiver power factor can only be lagging.

The angle of A is less than the angle of B for lines under one-quarter of a wavelength and also for lines between one-half and three-quarters of a wavelength so that for such lines synchronous power may be delivered at any reasonable power factor; while for lines between one-quarter and one-half of a wavelength and between three-quarters and a full wavelength the angle of A is larger than that of B and synchronous power, if delivered at all, can only be at a lagging power factor. For lines exactly one-quarter or one-half of a wavelength, the angles of A and B are equal when resistance is neglected and approximately equal when resistance is included. They are roughly 90 deg. and 180 deg. respectively. For these cases synchronous power may be delivered at unity or lagging power factor but not at leading.

Since the maximum power which can be transmitted at given terminal voltages will vary inversely as the magnitude of the constant B_o, the best operating conditions will be obtained with a frequency such that the magnitude of B_o is near its minimum value and the angle of B_o is greater than that of A_o by approximately 90 deg.

H. H. Skilling: Mr. Kroneberg has apparently not understood that "line transients" in the paragraph to which he refers are electrical phenomena. The mechanical oscillations of terminal machinery which are dealt with in "step-by-step, torque-angle, and voltage methods of studying stability" are slow compared to electrical transients. These methods generally assume the electric circuits to be continually in the steady state. After transmission line transients die out, the "transient" stability problem has in reality just begun.

Nor does he appreciate that maximum stability is needed only when the load to be supplied is large, and that therefore the optimum value of B_o need be reached only when all terminal machinery is in service.

It is true that large static condensers on high-voltage lines offer serious practical problems.

Intercontinental Radiotelephone Service
From the United States

BY J. J. PILLIOD*

Member, A. I. E. E.

Synopsis.—Radiotelephone service between the United States and Europe was established January 7, 1927 with one circuit and with service to limited areas. Facilities and service have been greatly improved and extended and rates have been reduced. Present scope of service is described and reference made to consistent increases in transatlantic telephone messages handled. This increase indicates that this service is being found of increasing value by the public.

Extent of ship-to-shore radiotelephone service from the United States is outlined. Arrangements for service to Buenos Aires and Rio de Janeiro are described, these differing from arrangements used for service to Europe in that operation to these two cities was planned on a part time basis. Proposed short-wave system for operation with Bermuda and proposed new long-wave system to supplement existing facilities to Europe are mentioned.

A description of the new radiotelephone transmitting and receiving stations now being erected at Dixon and Point Reyes, Calif., respectively, is given. These stations will be connected to a terminal office at San Francisco and the system used for the establishment of radiotelephone service to the Hawaiian Islands and later on, to other transpacific points as may be required.

* * * * *

SINCE January 7, 1927, when commercial radiotelephone service was first established between New York and London, there have been continuous and important developments in the application of radiotelephony for intercontinental communications as well as a generally sustained increase in the public demand for this class of service. Today the Bell System, in cooperation with the British Post Office, has four radiotelephone circuits to London, the original long-wave channel supplemented by three short-wave channels. By means of these, telephones in the United States, Canada, Cuba, and Mexico may be connected to practically any telephone in Europe, the city of Ceuta in Northern Africa, part of Australia, and Java in the Dutch East Indies. Service to all European points and Ceuta in Northern Africa is furnished through London where connection is made to the submarine cables and land line facilities making up the European telephone network. As yet Russia, Greece, Turkey, and a few of the Balkan States cannot be reached from the United States over this network. Service to Australia is given by switching the New York-London radio circuits at the latter point to a short-wave radiotelephone channel between London and Sydney, Australia. Service to Java is furnished through London to Amsterdam or Berlin, where connection is made to a short-wave radio channel operated between those points and Java by the Dutch Telephone Administration.

Transatlantic telephone messages between the United States and Europe during the first six months of 1931 were about 20 per cent greater than for the corresponding period for 1930. While the basic rate, which is the rate from New York to London for a three minute period, was reduced from $45 to $30 on May 11, 1930, the increase in traffic is considered very satisfactory in view of the general business conditions which have existed on both sides of the Atlantic, and is an indication that this service continues to be of increasing usefulness to the public.

In December, 1929, a ship-to-shore short-wave radiotelephone service was established on a commercial basis through New York with the *S. S. Leviathan.* Since that date service has been opened with five more of the larger liners plying between North America and various European ports. The additional ships are the *Olympic*, *Homeric*, *Majestic*, the *Belgenland*, and the *Empress of Britain.* While this service is normally furnished, at present, with ships only in the Atlantic area, contacts were made last winter with the *Belgenland* during a large part of its cruise around the world and with the *Homeric* then cruising in the Mediterranean.

The Bell System, cooperating with the International Telephone and Telegraph System, established on April 4, 1930 a short-wave radiotelephone channel between New York and Buenos Aires. Through Buenos Aires service may be given by land line connections not only to other parts of the Argentine Republic, but also to the great majority of telephones in Uruguay and Chile.

Construction has been completed recently to the end that the South American Service may be enlarged to include Rio de Janeiro, Brazil. The plans for the radiotelephone system to work with Rio de Janeiro are on a somewhat different basis than for the services established heretofore from the United States and it may be of interest to outline briefly the arrangements made. The previously established services contemplated the full-time use of one or more complete radiotelephone circuits whereas service to Rio de Janeiro is planned on the basis of sharing facilities already provided for service to Buenos Aires. In the United States the transmitter operating with Buenos Aires has been provided with an additional antenna directed toward Rio de Janeiro and at the receiving station there has

*American Tel. & Tel. Co., 15 Dey St., New York, N. Y.

Presented at the Pacific Coast Convention of the A. I. E. E., Lake Tahoe, California, August 25-28, 1931.

been installed a complete new receiving unit adjusted to receive from Rio de Janeiro. At the transmitting station switches are provided for rapidly changing the transmitter from one antenna to the other while at the receiving station the two receiving units make it possible for the New York control office to keep in constant touch with both distant transmitters. This arrangement allows for the maximum use of equipment and facilities and seems to offer a promising means of providing for the extension of radiotelephone service to a number of points to which it may be desirable to furnish service but where the cost of apparatus for full-time channels cannot at the time be justified. This arrangement also offers an opportunity to reduce the number of frequency assignments required as a number of points may be served from one transmitter using the same transmitting frequencies where the conditions permit. It is expected that this general method will find considerable application in economically extending existing services as by merely providing the necessary antennas and receivers, one set of transmitting equipment, which is the expensive item, can be used for service to a number of points to the extent that the traffic loads permit.

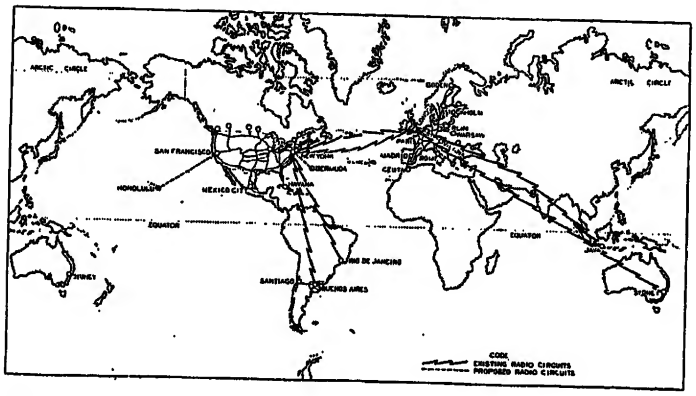

FIG. 1—INTERNATIONAL RADIOTELEPHONE CONNECTIONS OF THE BELL SYSTEM, AUGUST 1931

The radiotelephone services previously referred to and which have been established to date now make it possible for telephone users in this country to be connected to more than 91 per cent of the world's telephones. From the map shown in Fig. 1 it may be seen that these existing facilities provide the ground work for furnishing telephone service from North America to the east and south. Preliminary studies have been made of the possibilities, probable demand, and usage of telephone service from the United States to all parts of the world. A world-wide service of this kind is something that is extremely interesting to contemplate but it is also obvious that while considerable progress has been made in establishing such a service, an objective of this magnitude must be approached with due consideration to such factors as equipment and antenna development, costs, probable usage, differences in time and languages, and availability of satisfactory wavelengths.

In line with the desired objective of extending this service where practicable plans have recently been completed and the construction work is now in progress to establish in conjunction with the Imperial and International Communications, Limited, a short-wave radiotelephone channel between New York and Hamilton, Bermuda, there to connect with the land line facilities serving the Bermuda Islands. This radio circuit will, in general, closely resemble the other short-wave radio circuits previously established. The transmitter will be considerably smaller and of lower power since the distance to be covered is only about 700 miles compared to about 3,400 miles between New York and London, 4,800 miles between New York and Rio de Janeiro and 5,300 miles between New York and Buenos Aires. It is expected that the Bermuda system will be ready for operation late this year.

During the past year and a half the Bell System has acquired right-of-way and has constructed two test antennas at Bradley, Maine, near Bangor. These test antennas were constructed for experimental purposes looking forward to supplementing the existing New York-London long-wave circuit now working at 60 kilocycles with an additional long-wave circuit operating at 68 kilocycles. These antennas have proven effective at Bradley and plans are now in progress for the construction of a new long-wave transmitting station at that point. The receiving station for the additional long-wave circuit is planned for Houlton, Maine, the receiving point for the existing long-wave circuit. Owing to the magnitude of this undertaking it is expected that about three years will be required to construct the new long-wave system.

In the Pacific area the points which might logically in the future be furnished direct radiotelephone connection with the United States include the Hawaiian and Phillippine Islands, Japan, China, Australia, New Zealand, and Alaska. A transpacific short-wave radiotelephone system is now under construction, joint arrangements having been made with the Mutual Telephone Company of Hawaii to set up the initial circuit from California to Hawaii. It is a purpose of this paper to furnish some information about this system and particularly the arrangements at the California terminal.

The establishment of an overseas radiotelephone system on the Pacific Coast required, first of all, the selection of station sites for transmitting, receiving, and terminal control stations. A general survey of the west coast of the United States was, therefore, undertaken during the early part of 1930. This survey covered an area extending from a point north of Seattle to a point south of Los Angeles and inland for approximately 100 miles and included in addition to detailed studies of contour and road maps, a physical inspection of much of the area involved. It may be of interest to enumer-

ate here a few of the requirements for transmitting and receiving station sites which were given consideration in this survey. It will be noted from these requirements as well as from the descriptions of buildings and equipment which follow that the establishment of a permanent short-wave radiotelephone system planned to furnish commercial telephone service to a number of points is an undertaking of appreciable magnitude and cost.

The transmitting and receiving station sites for commercial short-wave radiotelephony should preferably be separated by at least 25 miles and by not more than 100 miles, and be so situated that no directional receiving antenna need look toward a transmitter and no directional transmitting antenna need look toward a receiver. Furthermore the transmitting station should not be too close to a receiving station of another agency, nor the receiving station too near a transmitting station although transmitters should operate satisfactorily near other transmitters and receivers near other receivers. This requirement necessitated at the outset, consideration of the locations of existing radio transmitting and receiving stations on the west coast of the United States so that those areas could be avoided which might be expected to be subject to interference from existing stations as well as the areas which would be most susceptible to outside interference.

For a transmitting station site about one square mile of land was desirable to allow for possible future developments. The land should be relatively clear and flat as excessive unevenness will involve difficult and more expensive antenna construction. Except in special cases, low or swampy land is undesirable for radio station purposes. The terrain adjacent to the site in the direction of transmission should be clear and reasonably flat for one or two miles. Distant mountain ranges in front of transmitting antennas should not subtend an angle of more than two or three degrees. In addition a desirable transmitting station site should be reasonably near telephone connecting facilities, reliable power supply, good railroad and shipping facilities and reached by good roads.

For a receiving station site the primary consideration was freedom from outside sources of interference. Experience has shown that considerable interference to short-wave reception may be caused by automobile, airplane, and motor boat ignition systems, industrial electrical machinery, and power lines. These may best be guarded against by the selection of an isolated site. The receiving site should consist of approximately a square mile and be at least a mile from well traveled roads, electric railroads, and commercial establishments in the direction of reception. The land itself should meet about the same requirements as those given for the transmitting station. A receiving station site should, of course, be accessible from the standpoint of telephone facilities. It is also desirable to have good roads, railroad and shipping facilities and power within easy reach. These items are, however, in general, secondary to interference considerations.

From the above mentioned survey there resulted the tentative selection of several tracts of land, the physical characteristics of which fulfilled the general requirements. The next step was to obtain at each of these locations, radio field test data which would indicate their comparative desirability from a radio standpoint. These data indicated the desirability of a site in the Sacramento Valley near Dixon and about 20 miles southwest of Sacramento for a transmitting station and a site at Point Reyes, on the California Coast about 35 miles north of San Francisco for a receiving station. Tracts consisting of approximately 520 acres at Point Reyes and approximately 640 acres at Dixon were subsequently purchased.

The receiving station site has about a mile of ocean water front, with terrain of reasonably satisfactory contours and has outstanding advantages from the standpoint of isolation and radio reception. Adequate power supply is available within a half mile of the property and telephone connecting facilities are being made available by a small amount of construction.

The transmitting station site is about four miles southeast of Dixon. The land is very flat, having a deviation of less than 10 feet in elevation over the entire property. The surrounding country is also essentially flat. This site is so located that power is supplied directly from a 44-kv. substation in Dixon which in turn is tied in with the Vaca-Dixon concentration station about eight miles distant. For telephone connecting facilities the site is also well located as the San Francisco-Sacramento telephone cable crosses the property.

With the selection and acquisition of transmitting and receiving station sites only the terminal control point remained to be fixed. San Francisco was selected as the most logical location since it is a large telephone center and occupies a strategic position in the nation-wide telephone network.

At the transmitting station the main building, Fig. 2, is located near the center of the property and is a two story fireproof structure of stucco on reinforced concrete and brick, approximately 40 by 60 ft. It is designed initially to house two transmitters with provision for extension as desired. There is a partial basement for heating facilities and a penthouse on the roof which contains the blowers and radiating system for use in cooling the water for the high power water-cooled tubes. On the ground floor are located the high-voltage transformer vaults, power entrance compartments, rotating machines associated with the transmitters, and battery and battery charging apparatus to furnish power supply for the voice-frequency equipment. Initially only one transmitter is being installed. This is located on the second floor as is also the line terminal or voice-frequency equipment for connecting the wire lines to the transmitter.

The transmitter is of the same general type as those located at Lawrenceville, N. J., and used in the transatlantic service. The transmitter proper consists of a number of individually and carefully shielded units mounted side-by-side. These units include a two-stage audio frequency amplifier, a Piezo electric quartz crystal oscillator with associated amplifier and harmonic generator stages, a modulating amplifier, and a two-stage radio frequency power amplifier. The output of the two-stage audio frequency amplifier is used to modulate the plate voltage of the modulating amplifier which uses two 250-watt tubes in a push-pull circuit. The carrier supply for this modulating amplifier is obtained from the harmonic amplifier stages which are driven by the crystal oscillator located in a temperature controlled oven in order to insure the maintenance of the carrier frequency within narrow limits. The output of the modulating amplifier is applied to the grids of the two-stage radio frequency power amplifier. The first stage of this amplifier contains two 10-kw. water-cooled tubes and the second stage contains six. The tubes are arranged in push-pull circuits and the entire system is carefully balanced to ground. The unmodulated carrier output power of the last stage amplifier is about 15 kw. which under conditions for 100 per cent modulation is equivalent to 60 kw. at the peak of the modulation cycle.

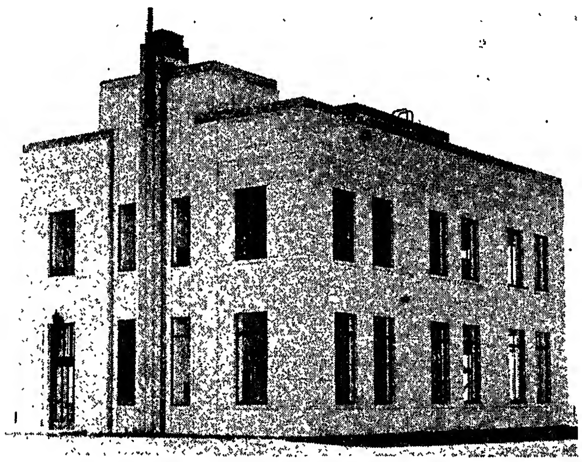

FIG. 2—TRANSMITTER BUILDING AT DIXON, CALIFORNIA

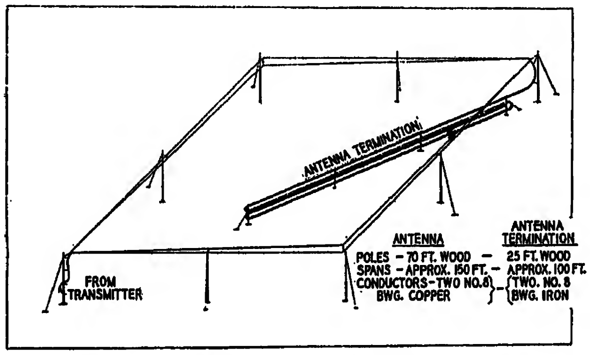

FIG. 3—SCHEMATIC OF HORIZONTAL DOUBLE-V TRANSMITTING ANTENNA

The power control board consists of nine panels and is equipped with the necessary meters, switches, and relays to remotely control and distribute all power to the transmitter.

Outside of the transmitter building is a power substation which transforms the incoming power at 11 kv. to 2,300 volts, the voltage supplied to the transmitter rectifier transformers. This power substation has sufficient capacity to care for two transmitters with an average power consumption per transmitter, including miscellaneous requirements, in the order of 150 kw. with a power factor of about 85 per cent. In the power substation are also located small transformer banks for lighting and miscellaneous power as well as circuit breakers and disconnect switches so that the building and transmitter power supply may be cut off if required.

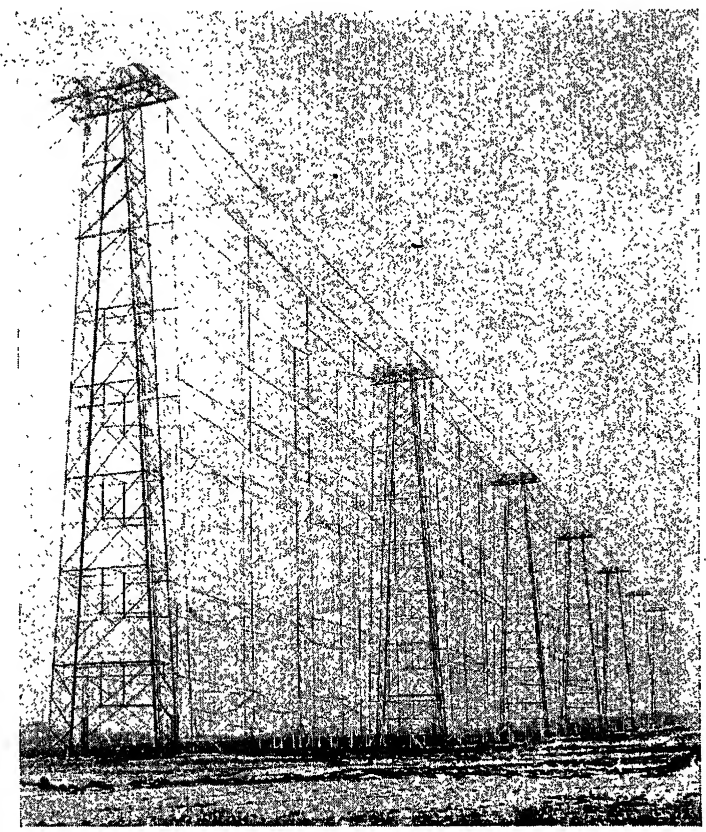

FIG. 4—ANTENNA TOWERS AND CURTAINS AT LAWRENCEVILLE, N. J., USED FOR SERVICE TO BUENOS AIRES

Three similar antenna systems are used with three radiotelephone channels to England

From the transmitter the radio frequency energy is fed over an open-wire transmission line to the transmitting antenna located about 800 ft. south of the building. The initial transmitting antenna for the Hawaiian service is of the horizontal double-V type,

Fig. 3, recently developed by the Bell Telephone Laboratories.[9] This type of antenna which was first installed for use commercially for transmitting purposes between New York and Rio de Janeiro is a diamond shaped structure consisting of one or more horizontal elements supported on wooden poles. The longer axis of the diamond is pointed toward the desired receiving station. The antenna is driven from the rear apex of the diamond and when suitably terminated at the opposite end has a good unidirectional characteristic. This antenna has another very desirable characteristic in that it is effective over a range of frequencies within certain limits. For transmitting to Hawaii the initial antenna is designed to handle two frequencies in the vicinity of 7 and 14 megacycles. The gain of this antenna while varying somewhat with the frequency being transmitted ranges from eight to 16 decibels as compared to a single element half wave vertical antenna. This is comparable to the results obtained from the antennas at Lawrenceville, a picture of which is shown

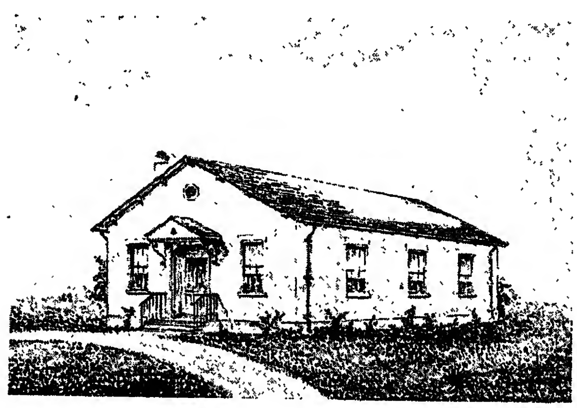

FIG. 5—ARCHITECT'S DRAWING OF RECEIVER BUILDING FOR POINT REYES, CALIFORNIA

in Fig. 4. When, however, it is considered that each antenna at Lawrenceville occupies two spans between the 185-ft. steel towers shown in the picture, and that each is effective for only the one frequency for which it was designed it may readily be understood that the horizontal double-V antenna which is of very simple construction is much more economical. The development of this relatively inexpensive antenna is of particular significance at this time because if radiotelephone service is to be opened to points which do not justify the provision of individual channels the number of antennas for use with existing equipment may be expected to increase materially in the next few years.

At the Point Reyes receiving station, Fig. 5, the building is a one-story semi-fireproof structure of reinforced concrete approximately 26 by 40 ft. so designed as to be capable of housing several radio receivers and their associated power and voice frequency equipment although only one receiver is being installed initially. The receiver building is located near the center of the property and about 2,000 ft. from the road. The receiver which is made up of a number of individually shielded units, mounted on four panels and assembled on four self-supporting racks, employs two stages of screened-grid radio-frequency amplification, a first detector, an intermediate frequency amplifier with input and output filters, a second detector and an audio frequency amplifier. From the output of the inter-

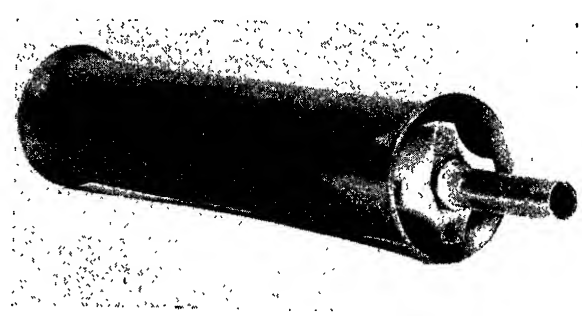

FIG. 6—SECTION OF CONCENTRIC COPPER CONDUCTOR TRANSMISSION LINE USED BETWEEN THE RECEIVING ANTENNA AND THE RADIO RECEIVER

Central conductor 3/8 in. outside diameter

mediate frequency amplifier a part of the received energy is diverted, put through a special two-stage intermediate frequency amplifier, rectified and supplied to the automatic gain control which in turn tends to keep the receiver output volume constant by controlling the bias potential on the radio frequency amplifier and the first detector grid circuits. In this receiver the first two panels which contain the equipment up to and including the first stage of intermediate frequency

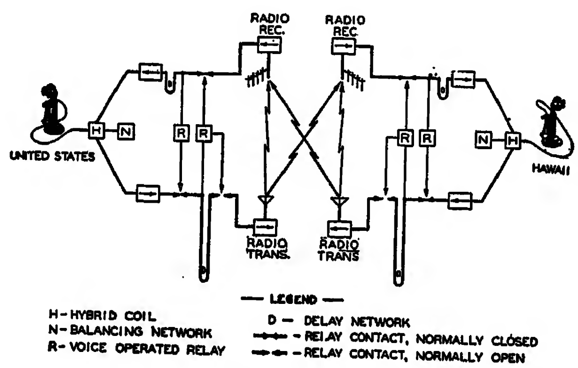

FIG. 7—TRANSPACIFIC RADIOTELEPHONE CIRCUIT

Fundamental arrangement of voice-operated devices

amplification are duplicates. By means of a switch the equipment in either of the first two panels may be connected to the rest of the receiver. This arrangement makes it possible to switch from one frequency to another with only slight tuning adjustments and, therefore, with the minimum loss of time.

Filament and plate battery is supplied to the receiver from small storage batteries provided in duplicate and so arranged that one set is on charge while the other is

supplying the receiver. Automatic regulation is provided in the discharge leads which holds the 24-volt filament battery voltage constant within plus or minus one-quarter volt and the 130-volt plate battery constant within plus or minus five volts.

The receiving antenna is also of the horizontal double-V type similar in construction to the transmitting antenna previously described. It is located about 500 feet northeast of the receiving building and is designed to receive two frequencies 16,195 kilocycles and 7,535 kilocycles. This type of receiving antenna is generally unidirectional and by virtue of this characteristic has a gain in the desired direction of reception about equivalent to the transmitting gain of the corresponding type of transmitting antenna. The receiving antenna is connected to the receiver by means of a concentric conductor transmission line run underground at a depth of about 18 in. This type of receiving transmission line is used because of its low transmission loss at high frequencies and because of the sheilding effect of the outer pipe conductor which is grounded. Fig. 6 shows an illustration of a short section of this type of transmission line. The outer pipe is 1⅝ in. outside diameter copper tubing and the inner pipe is ⅜ in. outside diameter copper tubing. The insulators or spacers are of Isolantite.

The terminal control station at San Francisco is located on the first floor of the Pacific Telephone and Telegraph Company's Grant Avenue toll building. To this location are brought the outgoing radiotelephone circuits to Dixon, the incoming radiotelephone circuits from Point Reyes, and the various telephone and telegraph order wires required for interstation communication. The equipment at the San Francisco terminal control station consists of a monitoring and testing position with volume control apparatus, vodas, delay, and privacy equipments with their associated testing and power supply panels.[5] The vodas equipment (voice-operated device anti-sing) briefly described consists of voice-operated relays which short circuit the transmitting line to the radio transmitter while the distant speaker is talking and short circuit the receiving line from the radio receiver while the local speaker is talking. This arrangement prevents interaction of the transmitting and receiving sides of the radio circuit. The delay equipment is designed to store up the incoming or outgoing voice currents for a fraction of a second until the vodas relay in the side of the circuit involved has had time to function and thus arrange the radio circuit for one way operation.

From the terminal control room the radio circuit is carried to a special position at the San Francisco toll switchboard where the traffic operator handling Hawaiian service is stationed. This operator has available before her a multiple of the toll circuits terminating at San Francisco and here connections may be made from the radio circuit to land line circuits extending to all parts of the country.

At the Hawaiian end the radio equipment of the initial circuit is to be furnished by the Radio Corporation of America and the general layout of the equipment is not essentially different from that at the United States end. Although it is not the purpose of this paper to describe this terminal, the transmitting station is located near Kahuku Point on the island of Oahu about 38 miles from Honolulu. The receiving station is located near Koko Head on the same island and about 12 miles from Honolulu at which point the terminal equipment is located.

It is expected that commercial service to Hawaii will be opened early in 1932. The establishment of this service will offer to the people of Hawaii telephone connection for the first time on a regular basis to the North American continent. In addition the establishment of the transmitting and receiving stations on the west coast will afford opportunities to make tests and obtain data leading to still further extension of radiotelephone communication to other transpacific points as may be decided upon in the future.

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Discussion

F. E. Terman: The double-V non-resonant transmitting antennas described in this paper represent an outstanding development in radio communication in that they provide an inexpensive highly directional antenna that can be used over a wide range of frequencies without readjustment. They also permit the same antenna to be used by different transmitters operating simultaneously on different frequencies.

There is one feature of these antennas in which I am rather interested. Being horizontally polarized, the horizontal double-V antenna is not capable of concentrating the radiation along the horizontal, which is generally considered to be desirable for long distance short-wave communication. I would like to know more about the effect which the angle of radiation has on the ability of the short waves to reach a distant receiving point. In particu-

lar, I wonder to what extent the effectiveness of the transmitter is reduced by concentrating the maximum radiation at angles in the order of 10 to 20 degrees instead of along the horizontal as is done by stacking broadside arrays as in the Lawrenceville antennas.

H. N. Kalb: What are the factors which determined the location at Dixon?

L. E. Reukema: Is progress being made in the reduction of the effects of static on long-wave radio telephone circuits, and can not improvement be made in short-wave transmission by suppressing the carrier?

Paul Ost: Why are the short-wave transmission characteristics from the United States to South America better than appears to be the case between the United States and Europe.

George T. Royden: The question has been raised of relaying over two approximately north and south circuits to avoid the difficulties experienced with an east-west circuit such as over the north Atlantic. The International System has such a circuit in operation handling telegraph business between New York and Madrid via Buenos Aires, with greater reliability than equivalent circuits over the north Atlantic.

The technical staff of the Bell System deserves much credit for the manner in which it overcame the many technical difficulties of providing commercially satisfactory transoceanic radiotelephone service. For instance, between San Francisco and Honolulu, the amplitude of the received signal frequently varies over a range twice as great as that perceived by the human ear. This is taken care of by automatic volume control and automatic switching of the circuit to one of the duplicate receiver and antenna systems which may at that moment be receiving the greater energy.

Radio engineers who have followed the cost of long range antenna systems during the past few decades, note with considerable interest the downward trend illustrated by high steel structures during the war period; a group of steel towers several hundred feet high just following the war period, a series of several antenna arrays on high wood poles during the past five years and now the simple double-V antenna supported by common wood poles only 70 ft. high and providing efficient operation over a wide range of frequencies. This development will permit the extension of communication facilities to many localities which could not be economically reached by other means.

Mr. Pilliod: The two horizontally polarized waves to be used at Dixon will be transmitted with an angle of approximately 15 and 30 deg. to the horizontal and will be determined largely by the distance to the Hawaiian station, and the wavelengths to be used. The conclusion that has been reached by the Bell System Engineers as to advantages to be gained by so-called under-modulation is that considering the service as a whole there is nothing to be gained by deliberate under-modulation and it has been concluded that the greatest advantage would be obtained by modulating the carrier wave as near 100 per cent as practicable.

Routing a short-wave radio circuit from New York to Europe via a point south from New York has been considered but taking all things into consideration including cost, the preferable arrangement so far has been to handle the service direct. Relays are of course now used in handling service from the United States to Australia and Java but this method introduces considerable complexity and some real difficulties.

The factors determining the location of the Dixon station are considered to be fairly well outlined in the text of the complete paper but, in general, locations of this kind are determined by economic considerations after the technical features have been satisfied.

Improvements have been made and others are contemplated to reduce the effect of static on long-wave systems. These are directed largely toward transmitting and receiving antenna designs, and it is hoped that the new long-wave system mentioned in the paper will have incorporated in it some of these improvements. While there would be advantages in some directions in suppressing the carrier in short-wave systems there are some disadvantages and so far, the Bell System practise and that of the other companies with which it cooperates, has been to transmit the carrier wave in the services operated from the United States.

As to north and south short-wave radio transmission being better than east and west across the north Atlantic, the times of variable results in the latter case are associated closely with times of magnetic disturbances and manifestations of aurora.

The San Francisco-Los Angeles Section of The Pacific Coast Telephone Cable Network

BY E. M. CALDERWOOD* and D. F. SMITH†

Member, A. I. E. E. Associate, A. I. E. E.

Synopsis.—In 1926 it became apparent that increasing demands for telephone service on the Pacific Coast would warrant the completion of a telephone toll cable between San Francisco and Los Angeles before the end of 1930. This cable, which is the longest west of the Mississippi and which with buildings and equipment represents an investment of approximately $10,000,000 is strategically located for giving service between points on the Pacific Coast and to points on the North American Continent and the Orient.

It was completed and placed in service September 2, 1930. It provides approximately 275 telephone circuits or about the same number as would three of the latest type of sixty-wire, six-arm open-wire toll leads fully equipped with three-channel carrier telephone systems, and, in addition, certain broadcast and telegraph facilities. Two hundred and seventy miles of the cable is in underground construction, practically all being conduit which was placed specifically for this cable and other similar cables which it is expected will follow. Equipment associated with the cable is placed in eleven buildings along the route, five of which were newly constructed for this purpose.

This paper describes the fundamental data used and the methods followed in engineering and locating the cable, the problems met in constructing outside plant and buildings, which were unique in the rugged and isolated section across the Tehachapi Mountains, and certain items of interest in regard to its operation and maintenance.

INTRODUCTION

TO COMPREHEND the extensions of long distance plant of The Pacific Telephone and Telegraph Company and Southern California Telephone Company during the past few years, it is necessary for one to have a brief knowledge of the character of the country served by these Companies.

In their territory, there are four major centers of population, namely, the triangle formed by Portland, Seattle, and Spokane on the north, the San Francisco Bay district in the center, the Los Angeles-San Diego Area on the south and the Sacramento-San Joaquin Valley Area. In addition to the above centers, there is a large number of mining and lumbering localities, some active and others entirely or partially abandoned, where there are or have been relatively heavy demands for service.

This geographical situation has led to the provision of "backbone" plant connecting the principal centers of population and the construction of a network of distributing plant to tributary communities. Prior to 1920 all of the plant had been provided over a period of slow growth and on a conservative basis, but beginning about 1920, the Pacific Coast entered a cycle of greater building activity and accompanying this were the related telephone demands which made it necessary to plan for the provision of a number of short toll cables in the vicinity of Los Angeles, namely, to Long Beach, Anaheim and Santa Monica, between San Francisco and San Jose in the central area, and between Seattle and Tacoma in the north.

In 1926 it became apparent that it would be necessary to further consider major toll additions for the main north and south route between Seattle and Los Angeles. Up to this time all relief on the main route had been obtained by the addition of open wire and by the superposition of carrier[1] telephone systems (an arrangement whereby in certain instances three additional talking circuits can be made available per pair of wires by the installation of special terminal equipment) where they could be employed.

Beginning in 1926, an acceptable program was developed for the Seattle to San Francisco route on the basis of open-wire and carrier additions, this plan being warranted because of the distances involved and the relatively small growth. Between San Francisco and Los Angeles, however, the problem was different because of the greater development, and to explain the decisions covering this route, it will be necessary to discuss the plant and facility situation existing at the time major relief measures were considered.

SAN FRANCISCO-LOS ANGELES OPEN WIRE ROUTES

There were two main open-wire routes (see Fig. 1) between San Francisco and Los Angeles; one along the Coast through San Jose, San Luis Obispo and Santa Barbara known as the "Coast Route," and one via Gilroy and the San Joaquin Valley through Fresno and Bakersfield called the "Inland Route." With the exception of two phantom groups (8 wires) on the Coast Route which were of 165 mil (No. 8 BWG) copper wire, all wire on both routes was 104 mil (No. 12 NBS) copper.

The Coast Route consisted of a 12-in. spaced phantomed[2] lead (an arrangement whereby two "side" circuits and a "phantom"[3] circuit are obtained from each group of four wires) bearing three through arms and transposed for carrier[1] operation. In general, the side and phantom circuits were used for the shorter haul circuits such as San Luis Obispo-Santa Barbara, while the longer haul circuits were handled over eight

*Plant Ext. Engr., Pacific Tel. & Tel. Co., San Francisco, Calif.

†Plant Ext. Engr., So. Calif. Telephone Co., Los Angeles, Calif.

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1. For references see end of paper.

type "C" carrier telephone systems providing a total of twenty-four channels suitable for longer circuits such as Los Angeles to San Francisco or Seattle. In addition to these regular services, two copper circuits were set aside for connecting radio broadcasting stations with studios originating programs, and one for picture transmission.[4]

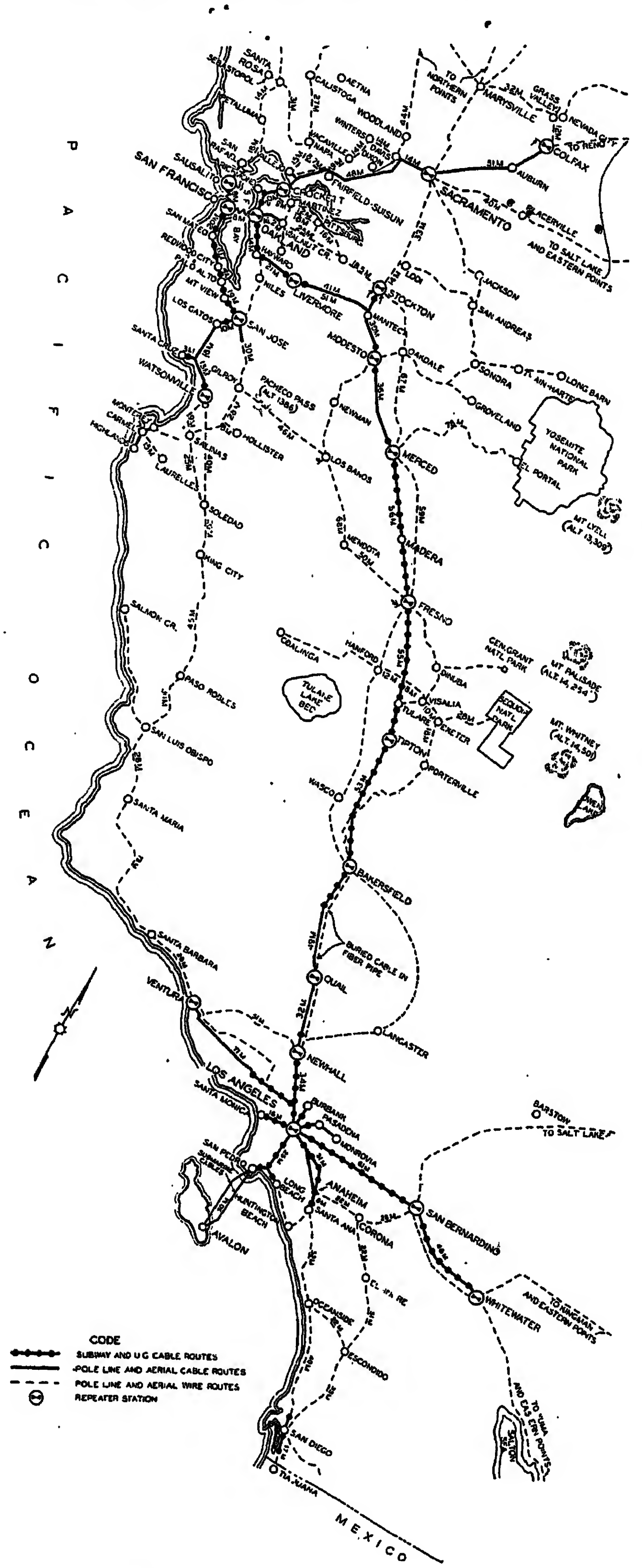

FIG. 1—MAP SHOWING OPEN WIRE AND CABLE ROUTES BETWEEN SAN FRANCISCO AND LOS ANGELES

The Inland Route via San Jose, Gilroy, Fresno and Bakersfield to Los Angeles carried two phantomed crossarms suitable for carrier and short haul service between San Jose and Fresno and a minimum of three arms from the latter point to Los Angeles. Seven type "C" carrier telephone systems, each providing three talking circuits, were operated between San Jose and Los Angeles over this route providing 21 channels for the longer circuits. In addition to these, carrier telephone systems were in use between San Jose and Fresno and between Fresno and Los Angeles for providing shorter haul requirements. One arm of open wire from Sacramento connected with the main inland lead at Fresno and provided for the superposition of two Sacramento-Los Angeles carrier systems furnishing four Salt Lake City-Los Angeles and two Sacramento-Los Angeles circuits. Two program circuits between San Francisco and Los Angeles were routed over the Inland Route, as well as an emergency assignment for the picture circuit.

In addition to these telephone arrangements, a certain amount of telegraph operated simultaneously over these leads, providing private-wire telegraph services to brokers, press associations, and others. The backbone telegraph circuits were supplied by four carrier telegraph systems (two over the Inland Route and two over the Coast Route) each of which provided ten 60-speed (60 words per minute) telegraph circuits suitable for teletypewriter operation between Oakland and Los Angeles. Also a small number of telegraph circuits, used principally for teletypewriter at a speed of 40 words per minute and for manual telegraph, were superposed on the two leads by "compositing," an arrangement enabling a telegraph circuit to be obtained from each of the two wires of a telephone circuit by the addition of special equipment.

The annual growth in telephone circuits, as estimated in 1927 was on the order of ten through or long haul circuits and varying numbers of shorter circuits depending on the location. This growth was such that it was impossible, without large expenditures and unreasonably large carrying charges to take care of the requirements by additions to the open-wire leads beyond the end of 1930.

RELIEF MEASURES

Since the relief required involved appreciable expenditures, a number of suitable plans for providing it was developed. These included:

1. String additional open wire, retaining phantom circuits and superpose additional carrier telephone systems.

2. Change one or both of the present leads to a non-phantomed[2] basis, providing for carrier operation on all arms. Under such a plan, the phantoms on all pairs

except the pole pairs would be sacrificed and the spacing between the wires of each pair would be shortened, but the lead would be so transposed that carrier could be superposed on all non-pole pairs. As an example, a 40-wire lead provides 30 voice-frequency and 24 carrier circuits making a total of 54 circuits where phantoms are retained, whereas it provides 70 on a non-phantom basis with maximum carrier application.

3. Construct a new non-phantomed open-wire lead.
4. Place a toll cable.

The first two plans were discarded because of the fairly high rate of circuit growth and the relatively small amount of relief obtained for the expenditure required. The third plan appeared more attractive but here again the growth was of such magnitude that after all carrying charges were considered, the plan was unattractive and accordingly discarded. As a final measure, the provision of relief by cable was considered and this plan was ultimately adopted.

A cable for a certain period furnishes a surplus of facilities, and accordingly it affords a more flexible arrangement for handling unanticipated circuit demands and as the circuits are not subject to trouble from line swings and other interferences affecting open-wire circuits, a more reliable service results. In general, cable circuits are less subject to interference from power exposures and consequently are quieter than those in open wire, being comparable in this regard to carrier circuits. Also the concentration of facilities on one route makes it easier to avoid high-tension power exposures, economical to make larger underground extensions, and insures minimum maintenance expenses which are in general proportional to the mileage of supporting structure. Balanced against these advantages is the possibility in case of failure that a greater number of circuits may be out of service than is the case of open wire, but with modern maintenance methods, this is not considered to be a serious factor.

In addition to caring for short- and long-haul voice-circuit demands, a cable will provide satisfactory circuits for telegraph, radio program supply, and picture transmission.

As a basis for the cable relief, studies were undertaken covering the telephone development along the desirable routes between San Francisco and Los Angeles, which included the Coast Route (435 mi.); the Valley Route (412 mi.) by way of Oakland, Modesto, Fresno and Bakersfield; and a Combination Route (425 mi.) by way of San Jose, Gilroy, and Fresno, paralleling the Inland open-wire route.

A portion of each route passes through highly cultivated country and in each case high-voltage power line development is considerable. It is perfectly feasible to find routes where private right-of-way costs are reasonable and which are not subject to power interference but these routes are also well removed from the market for telephone service. Private right-of-way costs in the vicinity of areas of extensive telephone development are excessive and the occupancy of highways with aerial plant is undesirable due to power interference and possible maintenance costs arising from changes in highway alinement. There was little advantage from these standpoints in regard to any one of the proposed routes.

It was found that, excluding the telephone stations in San Francisco and Los Angeles and the points immediately tributary to them, the telephone development along the Valley Route was greater than that on the Coast Route or the Combination Route. In addition, along the Valley Route, toll requirements as well as station growth, were greater than for the other routes.

Furthermore, there was a serious facility shortage between the San Francisco Bay area and Fresno which

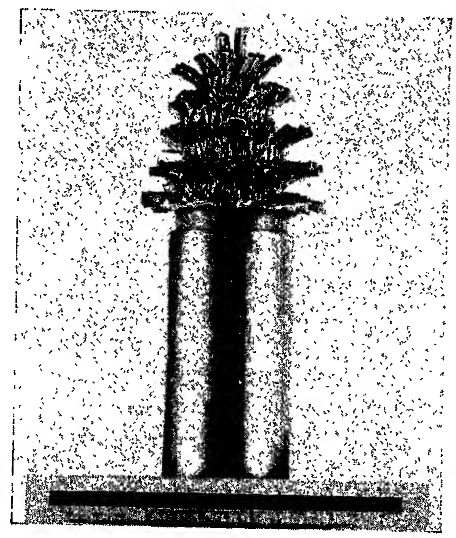

Fig. 2—Full Size Toll Cable with Sheath Partly Removed Exposing Interior Arrangement

required immediate relief. Between Fresno and Los Angeles the short haul circuit demands were not so pressing, but other factors such as highway widening necessitated major relocation projects.

In view of these conditions and the fact that the shorter length of the Valley Route would effect a considerable saving, it was decided that the most advantageous relief plan would be to follow the Valley Route.

Engineering Fundamentals

In the Bell System the cables standardized for toll projects, exclusive of submarine, are, in general, of paper insulated 16- and 19-gage conductors having a sheath composed of a lead-antimony alloy, and available in a number of sizes and combinations of conductors. In the case under discussion, circuit requirements were such that a "full size" cable (2.6 in. external diameter) was warranted. Full size cables (Fig. 2)

weigh approximately 7.6 lb. per ft. and the sheath thickness is 0.125 in. Spirally wrapped paper insulation is first applied to each wire and then two wires are twisted together to form a pair. In turn, pairs are twisted together in groups of two to form "quads," the unit dealt with when it is desired to use phantomed[3] operation which enables three-voice paths to be derived from two pairs. In order to decrease the attenuation or transmission loss, "loading"[3,5,6] coils, contained in cast iron or welded steel cases are associated with each pair at regular intervals along the cable. These loading coils consist of series inductances and, since telephone cable circuits are highly capacitative, have the effect of improving the efficiency of the circuit for transmitting voice-frequency currents.

The basic coil spacing adopted for this project was 6,000-ft. or H spacing for the Oakland-Los Angeles section. In addition to the H spacing, B or 3,000-ft. spacing was desired for certain purposes and the loading was so laid out that alternate B points coincided with the H points. This arrangement was important since special loading manholes in the underground sections and special fixtures in the aerial sections of the cable must be constructed for the loading coil cases. For the submarine section under San Francisco Bay, it was necessary to adopt a special spacing of 12,000 ft. since submarine coils were impracticable in the depths considered and it was feasible to obtain this spacing by locating a loading point on Yerba Buena Island in San Francisco Bay. The loading coil cases were fairly accurately located to meet the spacings given above.

The improvement obtainable by the application of the "lumped" loading described above, cannot be extended indefinitely and practically the limit[6,7] is soon reached. Very exhaustive studies by Bell System engineers in which transmission improvement has been balanced against cost has led to the standardization of a very few types of loading.

Three of these standard loading systems were selected for use on the Oakland-Los Angeles section of the cable. One (known as the H-44-25 loading system) is used for very long haul service and consists of 44 mh. coils on sides and 25 mh. coils on phantoms, these coils being placed on H or 6,000-ft. spacing. This loading is placed on 19-gage wire and the facilities so obtained are operated on a "four-wire" basis (*i. e.*, separate paths for the two directions of transmission).[3,7] Having separate paths for transmitting in the two directions enables greater amplification to be employed at repeater offices and greater freedom from difficulties due to electrical reflection or echoes[7,8] results. However, with the longer four-wire circuits, it is still desirable to install equipment which eliminates the echo return path. These "echo suppressors"[8] are installed at Fresno which is approximately midway between San Francisco and Los Angeles. The next loading system, in order of decreasing excellence, consists of the same weight coils placed on the same spacing on 16-gage wire, the actual loading differing only in slight adjustments for crosstalk. These facilities are used on a "two-wire" basis (*i. e.*, the same path for the two directions of transmission). The third system of loading which has been used on either 16-gage or 19-gage wires provides circuits for relatively short haul only. This system of loading (known as the H-172-63) uses 172 and 63 mh. coils on the sides and phantoms, respectively, placed on 6,000-foot spacing. A fourth loading system (B-22) not yet in place is proposed for very high-grade service in transmitting programs to radio stations. This loading[9] is placed on 16-gage pairs and consists of 22-milhenry coils placed at 3,000-ft. intervals.

While loading decreases the attenuation of voice currents it is still necessary to amplify them at certain intervals on longer cable circuits. Amlpification is obtained by using vacuum tube amplifiers or "repeaters"[10] more or less regularly spaced along the cable. Due to the limits on the improvement obtainable by loading and the lower cost of smaller gage wires, it proves economical to place repeaters at about 50-mile intervals. There are three types of these repeaters which have been standardized. The first is the four-wire amplifier and consists of two independent amplifiers for the two directions of transmission. The second is used on two-wire circuits and consists of two one-way amplifiers (one for each direction of transmission) connected together through devices known as hybrid coils which separate the two directions of transmission.

The third type[9] of repeater is for use on the 16-gage B-22 loaded circuits transmitting programs for radio purposes. These are high quality amplifiers passing a very wide range of frequencies and are used for transmitting in one direction only.

The following points were selected for the repeater stations on the cable: Oakland, Livermore, Modesto, Merced, Fresno, Tipton, Bakersfield, Quail, and Newhall, repeaters also being used at the two terminals in San Francisco and Los Angeles. The shortness of the spacing between the repeater points at San Francisco and Oakland was justified for practical and economical reasons in connection with 22-gage cable in the submarine section.

Signaling in the cable is accomplished by the use of alternating current. As a general rule, 20-cycle current is used for signaling on the shorter cable circuits on which telegraph circuits are not superposed. For circuits over two-repeater sections long, 135- or 1,000-cycle signaling is used, depending upon the economies of the particular case. If 1,000-cycle signaling is used, it is interrupted at the rate of 20 cycles per second and has the advantage of passing through and being amplified by the repeaters. It does not necessitate equipment for relaying around the repeaters, which is the case for 20-cycle signaling current and for 135-cycle current on circuits over two-repeater sections in length.

High-grade 60-speed telegraph facilities in a cable

are furnished by using the voice-frequency carrier telegraph system.[11] This equipment operates in the voice-frequency range and requires one four-wire circuit for each system supplying twelve telegraph circuits. For shorter haul requirements up to about two repeater sections in length, it is usually desirable to use the metallic telegraph system[12] which either uses pairs, or paths obtained by compositing.

Cable Selection and Description

The individual circuits in the cables are designed to provide a predetermined grade of transmission on the basis of the general toll switching plan[13] which is the fundamental circuit arrangement used in the Bell System for the layout of the toll plant. In many instances more than one design will fulfil the requirements and in these cases the most economical one is selected.

It will be of interest here to note the estimated number of circuits required for one of the periods studied with the type of facilities adopted in each case for a typical repeater section.

Table I shows the results of a study of estimated circuit requirements for 1933 as estimated in October 1928, for the Newhall-Los Angeles section. These are interpreted in terms of quads on the basis of three circuits for each two-wire quad and one and one-half circuits for each four-wire quad.

TABLE I—ESTIMATED 1933 CIRCUIT REQUIREMENTS—NEWHALL-LOS ANGELES SECTION
(Study of October 1928)

		Quads required			
		2-Wire			4-Wire
Circuit group	No. of Circuits	16-Gage H-172-63	19-Gage H-172-63	16-Gage H-44-25	19-Gage H-44-25
San Francisco-Los Angeles	51				34
Los Angeles-Seattle	4				3
Los Angeles-Portland	4				3
Los Angeles-Sacramento	5				4
Los Angeles-Salt Lake City	10				7
Los Angeles-Fresno	12				8
Los Angeles-Visalia	5				4
Los Angeles-Porterville	2				2
Los Angeles-Bakersfield	18			6	
Miscellaneous transcontinental	12				8
Voice-frequency telegraph	6				4
San Francisco-San Diego	3				2
Los Angeles-Sandberg	1		1		
Los Angeles-Mojave	3		1		
Los Angeles-Lancaster	5		2		
Los Angeles-Palmdale	3		1		
Los Angeles-Fillmore	14		5		
Los Angeles-Newhall	7	3			
Eight type C Inland carrier systems	24	8			
Total requirements	189	11	10	6	79
Proposed cable facilities	249	13	21	6	86

Although generally desirable, it was not possible, because of differences in the circuit requirements and the different rates of growth in the various portions of the route, to install a cable with the same make-up in all sections. The make-ups decided upon are given in Table II.

TABLE II—CABLE MAKE-UPS

	Cable section			
	San Francisco-Oakland	Oakland-Stockton Jct.	Stockton Jct.-Fresno	Fresno-Los Angeles
CABLE MAKE-UP				
16 gage quads		33	33	19
19 gage quads		85	85	107
22 gage quads	82	1	1	1
16 gage broadcast pairs		6	6	12
LOADING ARRANGEMENTS				
16 H-44-25, 2-wire quads		26	24	6
16 H-172-63, 2-wire quads		7	9	13
19 H-172-63, 2-wire quads		49	25	21
19 H-44-25, 4-wire quads		36	60	86
16 B-22-N, broadcast pairs		6	6	12
22 2H-44-25, 2-wire quads	42			
22 2H-44-25, 4-wire quads	40			
22 Nonload, tracer quads		1	1	1
AVAILABLE CIRCUITS				
16 H-44-25, 2-wire		78	72	18
16 H-172-63, 2 wire		21	27	39
19 H-172-63, 2 wire		147	75	63
19 H-44-25, 4 wire		54	90	129
16 B-22-N, broadcast	†	6	6	12
22 2H-44-25, 2 wire	126			
22 2H-44-25, 4 wire	60			
22 Nonload, tracer				
Total circuits*	186	300	264	249

*Not including broadcast and tracer.
†Broadcast facilities across San Francisco Bay are taken care of in other cables.

Fig. 3 is a typical cross-section of the cable used between Fresno and Los Angeles showing the location

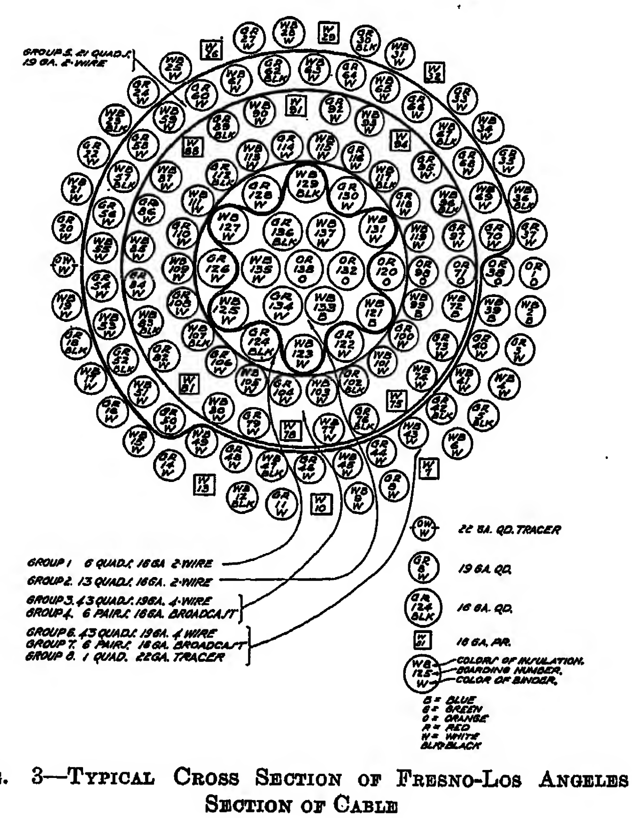

Fig. 3—Typical Cross Section of Fresno-Los Angeles Section of Cable

of the various quads and pairs contained in it, the coloring of the insulation which enables particular quads to be identified, and the system of numbering. The quads are arranged in layer formation with the 16-gage quads in the center. The twelve 16-gage broadcast pairs and the 22-gage tracer quad are interspersed in the first and third layers (counting from the outside) of 19-gage quads which are placed around the 16 gage. The heavy lines are shown merely to aid in visualizing the segregation of the various groups in the cable and do not represent a shield or separator of any kind. The tracer quad is used for test pairs during the construction period, and for making good any bad quad in a reel length.

The following schedule of completion dates was followed, which provided a reasonable manufacturing load and construction program, and a satisfactory realization of service dates when considered on a broad basis.

Section	Miles	Completion date
San Francisco-Hayward	23	1928
Stockton Jct.-Merced	57	1928
Hayward-Stockton Jct	55	1929
Merced-Fresno	55	1929
Fresno-Los Angeles	222	1930

The installation of the cable did not necessitate the immediate removal of the open-wire leads on the Coast and Inland routes, it still being desirable to temporarily retain all of these leads with a total of 16 carrier telephone systems for emergency and other purposes. The installation of the cable made it possible to carry out commitments to municipalities and to make clearance for highway widening between Newhall and Los Angeles by removing the open wire between these points. This made it necessary to transfer the Inland Route carrier terminals formerly located at Los Angeles to Newhall, extending the voice circuits derived from them to Los Angeles in the Newhall-Los Angeles section of the toll cable. A complement for this purpose was included in the studies for the Newhall-Los Angeles section, Table I.

Location of Cable

Studies of the proposed cable route indicated that a combination of aerial and underground construction would provide the best arrangement.

The location of the aerial plant was dependent to a large extent on the terrain and the presence of high potential power systems. Highway routes were available for much of the distance, but if the plant were located on these it would be subject to high maintenance costs. Private right-of-way routes were available in many sections, but their use had to be carefully justified in view of higher construction costs due to the character of the route and the cost of the right-of-way which was an appreciable item. Balanced against these costs was the fact that maintenance expenses could be expected to be lower due to less outside interference and less plant mileage. In locating plant, cost factors are used as a guide, tempered with sound engineering judgment and careful weighting of the factors which it is difficult to evaluate in terms of money.

The route finally selected (Fig. 1) consisted of 138 miles of aerial and 270 miles of underground construction, exclusive of the submarine section under San Francisco Bay. With the exception of 18.6 miles of fiber duct on private right-of-way south of Bakersfield, all of the underground was of clay duct construction. The principal sections of the route on private right-of-way occurred between Hayward and Stockton Junction and between Bakersfield and Newhall. Both sections are hilly and the use of a private right-of-way rather than a highway route could be justified on the basis of the savings in cable mileage.

Between Merced and Madera the cable parallels an 11-kv. circuit of the San Joaquin Light and Power Corporation at a separation of about 150 feet for a

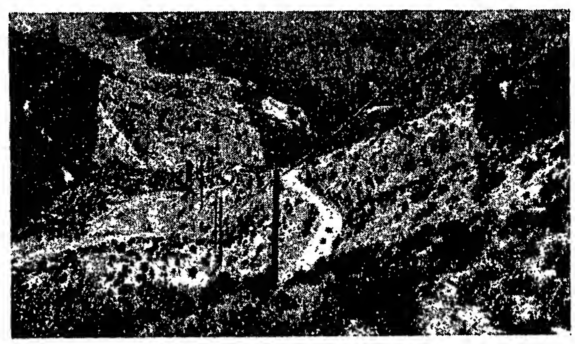

Fig. 4—View of Cable in the Tehachapi Mountains

Showing the general type of territory traversed, the construction road, the cleared right-of-way, and, at the upper left, the open wire lead

distance of some 34 miles. This exposure was considered sufficiently severe to warrant some remedial measure, and a plan was developed jointly with the power company which provided for the breaking of the exposure into a number of sections and the reduction of its length by a reroute of a portion of the power line. The costs of this measure were borne jointly by the two companies.

For 57 miles between Bakersfield and Newhall the cable is carried aerially on a private right-of-way. Thirty-five miles of this is over the Tehachapi and Sierra de La Liebre Mountains (Fig. 4), passing through fairly rough country. Some of the interesting problems encountered are described later in detail.

The right-of-way in this section was purchased from private owners or obtained over government lands and was 100 ft. or more in width. In most instances, the cable was placed in the center of the right-of-way, but on hillsides subject to fire hazards from brush, the poles were set above the center line.

The route was selected to be as short and direct as possible consistent with accessibility and economy. The most desirable location leading through fairly direct canyons and passes had to be avoided due to the presence of a 220-kv. high-tension power line from which a maximum separation was desirable to avoid inductive interference. The Ridge Route Highway, a scenic motor artery, which in general follows the summits of the ridges, was also impracticable due to the length of the circuitous route over the tops of the mountains.

The route finally taken parallels in general the Inland open-wire pole line through the mountains, although no attempt was made to follow this line and numerous departures occur at points where more advantageous locations could be found. In these mountains, elevations of 4,500 feet are encountered, the area is subject to heavy snow and occasional sleet during the winter months and, in accordance with Bell System standards, is classified as a "medium loaded" area.

Construction Problems in Tehachapi Section

The country traversed in this section is generally desolate and uninhabited, there being practically no roads within a reasonable distance of the route. While accessibility had, of course, been considered as far as practicable in selecting the route, special measures remained to be devised over most of the distance, and this phase of the work required considerable study and organization.

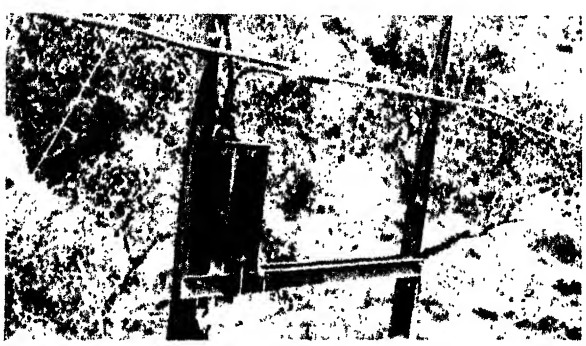

Fig. 5—Close Up of Cable and Loading Coil Case

Since all the conductors in the cable at this point were not loaded initially, the conductors were "ballooned out" within the extra splicing sleeve shown, to provide slack for splicing subsequent pots

The Ridge Route Highway following the general route of the cable is of but little value as a transportation route as the line is, in general, inaccessible from it, so it was necessary to build a total of about ten miles of new road and to widen and grade some nine miles of existing narrow dirt roads and paths. These roads were built as economically as possible, bearing in mind that they would be required for line maintenance and future construction.

The nearest railroad station from which the material could be hauled was Lancaster, located on the Mojave desert to the east. From this point a satisfactory road extended for about 40 miles toward the line, from where special transportation equipment was used over the construction roads. From the railroad delivery point at Lancaster, the principal items of material were transported to the job in a series of three steps. Ten-ton, six-wheel trucks and trailers hauled the material over as much of the distance as was accessible to them and then two and one-half ton trucks with drives on all four wheels and, in some instances, tractors and trailers, were used to deliver the material to its point of use.

As the existing open-wire lead carried the maximum wire load for which the poles were designed, namely, four crossarms, it was impossible to consider it for the support of the proposed cable. Considering the growth, it appeared reasonable to build a new pole line capable of supporting three cables and after an analysis of various types of supporting structures, fully-treated Douglas Fir poles normally spaced 110 ft. apart were selected. This particular type of pole was chosen because of its fire resistant qualities, resistance to termite attack and decay, its high fiber strength and reasonable cost.

The lead was built with 25-ft. poles. However, in order to maintain a proper grade and to care for numerous long spans, it was necessary in some instances to use poles as long as 60 ft. While the normal span of the lead was 110 ft., some spans as long as 510 ft. were constructed and required special designs and construction methods. The loading coils were supported aerially on special loading coil fixtures (Fig. 5).

Trucks (four-wheel drive) equipped with earth-boring machines and derricks were used for digging holes, setting poles and pulling cable in accessible locations. A considerable portion of the line was so located that hand digging was required and in many instances rock was encountered making the use of powder necessary.

The pulling of the cable presented interesting problems in many locations where the terrain was particularly irregular or steep. In general, the trucks with a four-wheel drive were used, but in some instances where these were not suitable, tractors especially equipped for pulling cables were employed. In pulling the strand and cable on steep grades, the general procedure was to locate the cable reel at the lower level and to pull the cable up the grade as the cable was then under control, the load being under tension during the entire pull. If it is pulled down grade, its weight must be controlled, the danger of its getting away becoming progressively greater as the pull nears completion.

The reels (weighing with cable about 6,000 lb.) were mounted on two-wheeled trailers specially designed for transporting and unreeling the cable and were delivered by trucks or tractors (Fig. 6). In some instances where the desired location for setting up the reel at the bottom of a steep grade was not accessible, it was necessary to lower the trailer with the reel down the slope on a

winch line, with the tractor at the top of the grade checking the descent (Fig. 7).

Some of the grades encountered were much longer then the normal reel length of 750 ft. and in such instances it was necessary first to lower the trailer and reel to the bottom of the grade with a tractor and then to lower a smaller tractor down to the point at which the pull was to be made. The small tractor was held in position while it proceeded to "dig-in" on the side of the grade and establish itself, after which it pulled the cable up to the point at which it was located. When

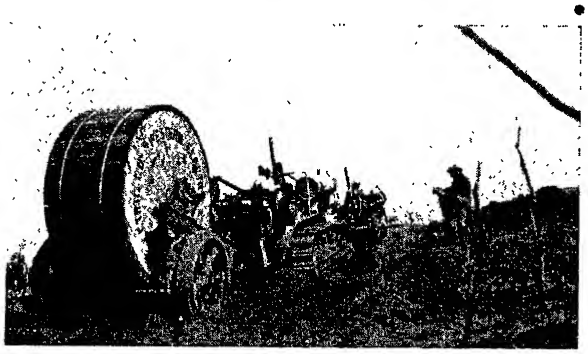

Fig. 6—Tractors and Trailer for Handling Cable Reels

this pull was completed, the small tractor was drawn back up to the top of the grade and a second reel was lowered on a trailer to the point where the small tractor had been previously located and the cable on the latter reel pulled in place.

Naturally some of the locations where loading coil cases (weighing as much as 1,675 lb.) and poles were to be installed, came on steep grades and in such instances special rigging and careful handling was often required, it being necessary in some cases to rig temporary spans of winch line across ravines or canyons with special slings devised to carry the cases to their ultimate position.

Use of Gas Pressure in Cable Sheaths

The insulating qualities of the paper strip used for the electrical separation of the conductors of a telephone cable are entirely dependent upon the exclusion of moisture. For this reason it is essential that the cable sheath be made moisture-proof and maintained in that condition.

Methods which have proved valuable during the past few years make use of gas pressure applied within the cable. Dry compressed nitrogen has been selected for this purpose because of its chemical inactivity, low cost, and lack of moisture content. It is supplied in 100-cu. ft. tanks, with a small regulating outfit, consisting of valves, hose, couplings and pressure indicator for controlling the admission of the gas to the cable.

In general, each reel of cable was tested after being pulled into place and before opening the sheath at the ends preparatory to splicing, by injecting the gas into it under pressure. With a pressure of 12 lb. per sq. in. throughout the cable length, any sheath opening was manifested by a drop in pressure and located with the aid of the hissing noise caused by the escaping gas. Then after each splice was completed, it was tested by forcing nitrogen under pressure through a small hole in the sleeve, any opening being indicated by bubbles in the liquid soap with which the sleeve was then painted.

A recent development is the use of continuous pressure in the cable after completion, with low-pressure alarm contactors spaced along the sheath at equal intervals. A drop in pressure in the vicinity of a contactor causes it to operate and close an alarm circuit in the cable which, in turn, sounds an alarm in the testing office. The gas escaping through the hole in the sheath prevents moisture from entering for a sufficient time to permit locating and repairing the hole. This method is in use in the fiber duct section south of Bakersfield.

Cable Layup and Testing

Early experimenters with telephone cables were both surprised and disappointed when they discovered that even for a cable only a few hundred feet in length, a telephone conversation taking place over one of the pairs could be heard well on the others. This condition, of course, resulted because all of the wires in the cable were placed parallel to each other, the development of the art not having progressed sufficiently to indicate methods for transposing pairs to avoid crosstalk. Elaborate means are taken in modern toll cables to reduce crosstalk between pairs and the picking up of noise from outside sources. These methods will now be described.

In a toll cable the various groups are kept separate, these groups retaining their identity throughout each repeater section. An example of this is shown in Fig. 3, where it will be seen that the four-wire group trans-

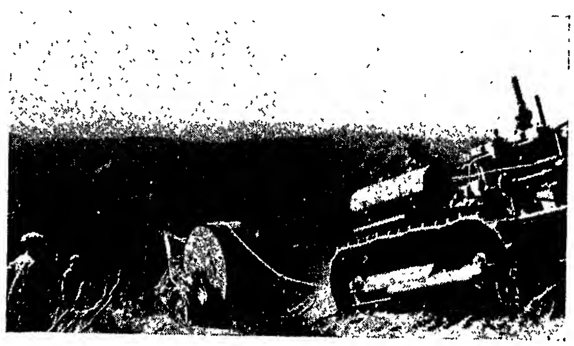

Fig. 7—Lowering Reel in Difficult Location

mitting in one direction (Group 6) is kept apart as much as possible from the four-wire group transmitting in the other direction (Group 3) by an intervening layer of two-wire (Group 5) 19 gage intended for H-172-63 loading. The broadcast pairs are located in the four-wire group transmitting in the same direction in which they are used.

As previously mentioned, the paper-insulated conductors in the cable are twisted together to form pairs,

two of these pairs in turn being twisted together to form a quad. This arrangement provides the initial transposing between circuits. In manufacturing the cable, three regular types of quads are made which differ from each other by the length required for the pair twists, and the length used per twist when the pairs are formed into quads. These different types of quads are used to further reduce the crosstalk between the circuits in the cable. To avoid the possibility of two quads in adjacent layers continuing beside each other, alternate layers are stranded in opposite directions during manufacture, the relationship between the layers, as shown in Fig. 3, being true only at exceptional points.

The standard reel length, used wherever possible, is approximately 750 ft. Fig. 8 shows the arrangement for splicing the cable in a normal 6,000-ft. loading section composed of eight reel lengths. When the cable is ready for splicing, the *P* splices are made first. These are known as "planned splices," at which the splicer joins particular quads in one direction to definite quads of the same group in the other. The plan for making the splice is prearranged, and the splicing pattern is so set up that different types of quads are spliced together, satisfactory separation of quads being effected and adjacencies between quads in other reel lengths being

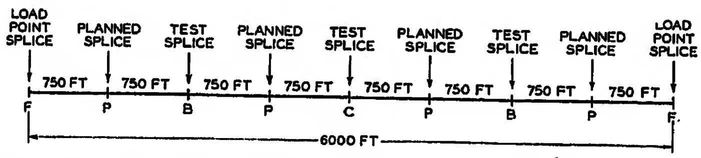

FIG. 8—TYPE AND LOCATION OF SPLICES IN NORMAL LOADING SECTION

minimized. Testers are then located at the *B* splices who measure the difference in capacitance unbalance[14] for the circuits in each quad. Quads in one direction are then spliced to quads of the same group in the opposite direction in such a manner as to neutralize the unbalances to the best advantage. The *C* or final test splice, for the loading section is then made in a similar manner. At the load points the loading coils are spliced into the circuit at random, the splicer connecting the loading coils between quads in the same group in accordance with no definite plan. In case the distance between the splices differs materially from 750 ft. on account of physical conditions, the above procedure is modified so that comparable results are obtained.

As described above, the four-wire group transmitting in one direction is kept separate from the four-wire group used for transmitting in the other. Because one of these groups is always nearer the sheath than the other, the effect of the rotation between the layers is that the length of the wires between two given geographical points is greater for those in the group nearer the sheath. In order to equalize this difference in length, which also results in equalizing the resistance and the transmission loss of the circuits in the four-wire groups which is essential since one group constitutes the return paths for the circuits in the other, a "transposition splice" is located approximately midway between repeater points at a *B* splice where the positions in the cable occupied by the two four-wire groups are interchanged; *i. e.*, groups 3 and 4 of Fig. 3 change places with groups 6 and 7. When the cable is in operation, the direction of transmission on the four-wire group is such that the output of the repeaters at the repeater stations is always applied to the group nearer the sheath, the greater energy thus being carried having the effect of reducing the noise to signal ratio. Its position at the same time shields the quads inside against noise.

In order further to reduce crosstalk between two-wire circuits, at each repeater point the cross-connections are so arranged that while the phantom circuits are connected straight through, the side circuits are systematically rearranged among the quads. A similar procedure is followed for the four-wire circuits, at the repeater offices which are located at the ends of circuit units.

It should be noted that the efforts to reduce the crosstalk described above do not result in its entire elimination, the result being that intelligible crosstalk is minimized, a small amount of unintelligible crosstalk, picked up from many other circuits and known as "babble," being left.

The measurements and tests[14] made on the sides and phantoms (after all the splices for a repeater section are completed, and the pairs with opens, crosses, grounds, or low insulation have been cleared or tagged) are the following: d-c. loop resistance, resistance unbalance, insulation resistance, crosstalk tests, transmission measurements at 1,000 cycles which are checked by calculated values, singing point tests, and impedance-frequency runs on those circuits which have a poor singing point. In general, impedance runs are made on a sample of from 5 to 10 per cent of the circuits in addition to the above, for the purpose of checking the correctness of loading and locating irregularities.

BUILDINGS AND EQUIPMENT

Eleven repeater stations were required for this cable, Livermore, Merced, Tipton, Quail and Newhall being new offices, and building additions being added at Modesto and Bakersfield. The other repeater offices (San Francisco, Oakland, Fresno and Los Angeles) were already in service, and it was only necessary to add the equipment associated with this cable. Each of the new buildings is so constructed as to harmonize with its surroundings, and locations were chosen, with the exception of Quail (which of necessity had to be located in the Tehachapi Mountains), which were readily accessible from established communities. The equipment contained in these offices is required principally for phantoming, ringing, amplifying and regulating purposes, and its extent may be appreciated from the fact that nearly 6,000 three-element vacuum

tubes were supplied initially, although, in many offices, sufficient equipment was installed to take care of only a part of the circuits which will ultimately be in service in the cable.

Of all these offices, Quail (Fig. 9), perhaps holds the greatest interest, because of the problems connected with finding a suitable location for it, in obtaining water, gas and power supplies, and housing for the personnel. The location of this station is near the Ridge Route Highway at the western end of the Antelope Valley,

FIG. 9—EXTERIOR VIEW OF QUAIL REPEATER OFFICE AND BUILDINGS

an arm of the Mojave Desert, at an elevation of 3,400 ft. In addition to the building for the equipment, which is of steel frame construction with reinforced concrete walls and roof, and the water tower, four modern houses equipped with electric refrigeration and unit heating systems were constructed for the personnel. With the exception of sand, which was obtained locally, all construction materials and telephone equipment were hauled by truck from Lancaster, the nearest railroad point 40 miles away, or from Los Angeles. Before construction could be started it was necessary to develop water, which fortunately was found in satisfactory quantities at depths of from 80 to 150 ft. All power required was generated locally until the middle of 1931, at which time commercial power from a substation, 30 miles away, became available. A high-pressure illuminating gas trunk line, operated by one of the gas utilities, passed nearby, and from this, gas for cooking and heating became available.

Fig. 10 is an interior view of the Quail repeater station showing four-wire repeater bays, test board, cross-connecting frame and other equipment which is typical of that contained in all the stations. Storage batteries (not shown in Fig. 10), providing a 24-hour power reserve for all of the equipment required for one cable and associated charging generators were installed. These generators are of the commercial type and in order to eliminate noise due to commutator ripple when the 24-volt batteries are being charged while in service, a filter consisting of a choke coil[15] and three electrolytic condensers[15,16] in parallel is installed in the leads discharging from the batteries to the equipment. The choke coil which has an inductance of approximately one mh. weighs about 650 lb. and is rated at 300 amperes. The electrolytic condensers have a capacity of from 800 to 1,350 μf. apiece, depending upon the frequency.

OPERATION AND MAINTENANCE

In operating the cable, it is convenient to establish "circuit units" which consist of circuits lined up for a definite transmission value between the offices designated as "circuit unit terminals" which are San Francisco, Modesto, Fresno, Bakersfield and Los Angeles. These circuit units are then patched together to form longer circuits, it merely being necessary to insert repeaters with the proper gain at the circuit unit terminal offices. In case of trouble on a through circuit, the particular circuit unit which is in difficulty can be replaced by a spare one with only a slight delay. Each circuit unit is under the jurisdiction of a control station (San Francisco, Oakland, Fresno and Los Angeles) which is responsible for keeping it up to the required transmission standard. Test wires are set up in the cable between the various repeater points to enable each station to converse with all others as required in lining up and maintaining the circuits.

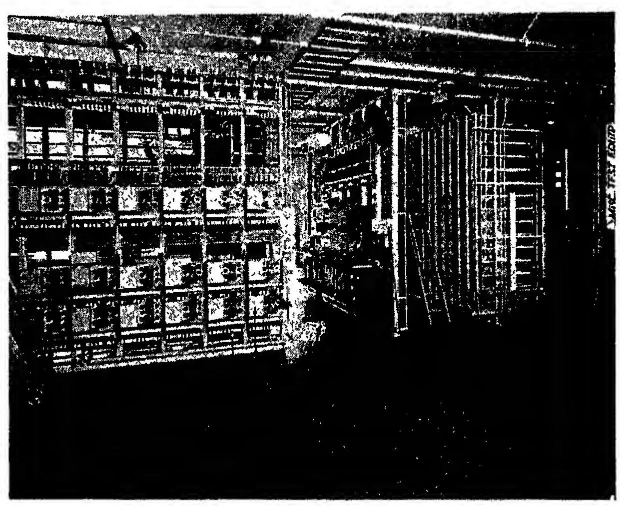

FIG. 10—INTERIOR VIEW OF TYPICAL REPEATER STATION

Due to variations in conductor resistance occasioned by temperature changes occurring between day and night and also those due to seasonal variations, the transmission loss may change for a San Francisco-Los Angeles four-wire circuit (normal loss, 9 db.) as much as 10 or 15 db. comparable variations taking place on all of the other circuits in the cable. In order to compensate for this, a "pilot wire regulating system" is installed in each circuit unit section. This consists essentially of a composited telegraph circuit or pair in the cable known as a "pilot wire," the resistance variations of which cause equipment in certain repeater stations (Livermore, Merced, Tipton and Quail) to func-

tion and automatically compensate for variations in all circuit units. The circuits are, of course, lined up for average temperatures and the regulators then provide for temperature variations in either direction.

Considerable testing equipment is required at each repeater office for maintaining the cable circuits at their highest efficiency. This equipment consists of wheatstone bridges, voltmeters, transmission measuring units[14] (for measuring the transmission efficiency of circuits and equipment), impedance bridges[14] (for locating line irregularities) and similar equipment. At Los Angeles a low insulation alarm system has been installed which brings in both a visual and aural alarm as soon as the insulation on certain selected pairs in the cable drops to a dangerous value. When this system indicates that the sheath has been damaged and moisture is slowly entering the cable and short circuiting out the pairs, the location of the trouble is determined by electrical tests and men are sent at once to repair it.

Future Extensions

It is expected that future demands for toll circuits on the Pacific Coast will result in greater major extensions to the long distance cable network. Several factors tend in this direction. One of these which makes it possible to contemplate greater extensions than in the past is the availability of tape armored cable[2] which may be placed directly in the ground without a subway structure. Another is the use of automotive equipment which makes the extension of heavy cable plant into rougher country possible. It is now feasible to undertake the extension of large-size cable over such rugged country as is encountered in the Sierra Nevada, Cascade, and Siskiyou Mountains. The application of such equipment has resulted in lower costs which, in turn, make greater extensions economically possible. Also the use of gas pressure in cables to indicate potential trouble makes it practicable to maintain cables through sparsely populated areas and provide reliable service.

These items and others, which will undoubtedly be realized in the near future, permit forecasting the extension of the coast cable network to connect the Seattle Area with the Southern California Area and the ultimate use of cable to connect the Pacific Coast cable network with that of the rest of the Bell System.

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Discussion

Glen Ireland: The authors, in connection with their description of the San Francisco-Los Angeles toll cable, also have indicated the general layout of the long haul toll plant on the Pacific Coast. In this connection it is of interest to note how completely this long haul toll plant on the Coast is now connected with that of the rest of the country, including the toll cable network extending over the central, eastern, and southern sections of the country. The major points of connection are at San Francisco, Los Angeles, and Seattle. From San Francisco and Los Angeles there are direct toll circuits to such points as Salt Lake, Denver, Kansas City, St. Louis, Dallas, Chicago, and New York City. San Francisco and Los Angeles together now have 14 direct circuits to Chicago and 13 to New York City. Seattle has direct circuits to such points as Minneapolis, Chicago, and New York City.

These circuits are carried eastward over separate open-wire routes and, allowing for construction now under way, will join the cable network again at Dallas, Oklahoma City, Kansas City, Omaha, and Minneapolis. In the open-wire sections practically all of these circuits are now provided by means of type C carrier facilities, the eight-inch non-phantomed open-wire construction being used in many repeater sections. Protection to this transcontinental open-wire network is provided by means of interconnecting toll routes extending, for example, north and south out of Salt Lake and Denver. The San Francisco-Los Angeles cable also provides a valuable tie-in for the transcontinental routes.

The toll cable network east of Minneapolis, Omaha, and Dallas provides innumerable possibilities of routing the circuits so as to insure continuous service. The problems of furnishing transcontinental service through this cable network involves many transmission problems, particularly those brought about by the time of transmission over long distances in cable. In this connection, the use of echo suppressors on the cable facilities, as mentioned by the authors, has been essential in overcoming the more important effects and in attaining the desired transmission results.

The Kindling of Electric Sparkover

Based on Lichtenberg Figures

BY C. EDWARD MAGNUSSON*

Fellow, A. I. E. E.

Synopsis.—A simple, experimental method is described for studying the kindling mechanism of electric sparkover. Experimental evidence is presented which tends to prove that electrons and not protons or positive ions are the active carriers in the kindling mechanism; that Lichtenberg figures form the initial step in the kindling process; that the sparkover channel develops from the positive Lichtenberg figure and that the sparkover path tends to follow the positive and negative Lichtenberg figures streamers.

THE mechanism of the electric sparkover process has lately become a much discussed problem. Townsend's theory of the formation of electric sparkover has been challenged and, at least in some respects, found wanting. Investigations by Rogowski,[1] Hippel and Franck,[2] Torok,[3] Marx,[4] Loeb,[5] Uhlmann,[6] Beams,[7] Schumann,[8] Slepian,[9] Peek and others give ample evidence that the sparkover process is very complex; that the speed of formation is in the order of 10^8 cm. per sec. instead of 10^4 or 10^5; that polarity and

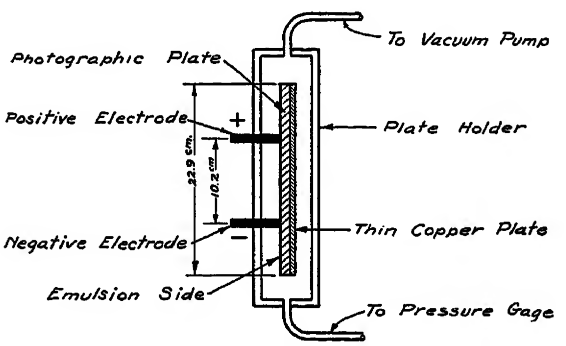

FIG. 1—CROSS-SECTION OF PLATE HOLDER

shape of electrodes, ionization, space charges, voltage gradients, air pressure, temperature and other factors enter into the problem. The results of investigations on the *early stages of electric sparkover* by Steenbeck,[10] Paavola[11] and particularly by Lawrence and Dunnington[12] throw light on certain phases of the initial or kindling stage of electric spark formation, but a comprehensive explanation of the mechanism or process involved in the formation of electric sparks or sparkover is still lacking.

In this paper a new method of approach is described and experimental evidence presented which tends to show that for *impulse sparkover* the following statements are valid:

a. That electrons are primarily the active elements in the kindling mechanism.

b. That Lichtenberg figures form the initial step in the kindling process.

c. That the sparkover develops from the tips of the positive Lichtenberg figures along the streamers of both the positive and the negative figures.

In connection with an investigation on the *effects of the magnetic field on Lichtenberg figures*[13] it was found that the same method could be used for obtaining evidence on the kindling process of electric sparks; that is, during the first few microseconds of the sparkover process.

The voltage impulse forming the Lichtenberg figures is impressed on the photographic plate located in a strong magnetic field, with the emulsion surface at right angles to the lines of force. Two electrodes, in the holder, spaced 4 in. (10.2 cm.), are in contact with

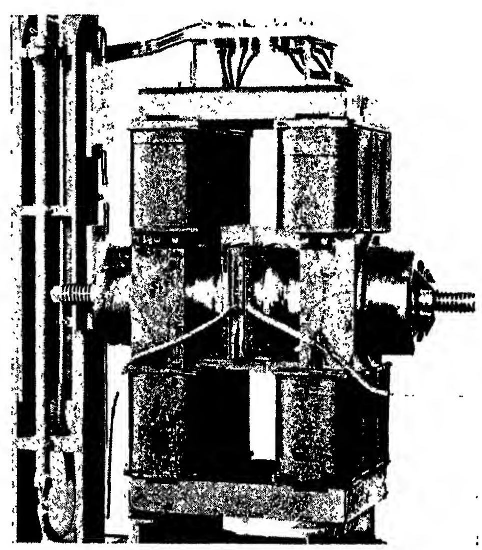

FIG. 2—ELECTROMAGNET WITH PLATE HOLDER IN POSITION

the emulsion side of the plate. The reverse side of the glass is in contact with a thin copper plate. A cross-section of the holder, with photographic plate in position, is shown in Fig. 1. The plate-holder is air-tight and the desired degree of vacuum obtained by a vacuum pump. An illustration of the electromagnet, with plate-holder in position, is shown in Fig. 2. The diameter of the circular pole-face is 10 in. (25.4 cm.); the pole spacing variable, but kept at 2 in. (5.1 cm.) for

*Prof. of Elec. Engg. and Director of Engg. Experiment Station, University of Washington.

1. For references see Bibliography.

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the figures in this paper, except Fig. 7 for which a smaller magnet was used.[13] Eastman: *Speedway* 6½ in. by 8½ in.; Lumiere: *Sigma* 5 in. by 7 in., and Eastman: *Hyper-sensitive pan-chromatic* 5 in. by 7 in., photographic plates were used.

The voltage impulse was obtained by the discharge

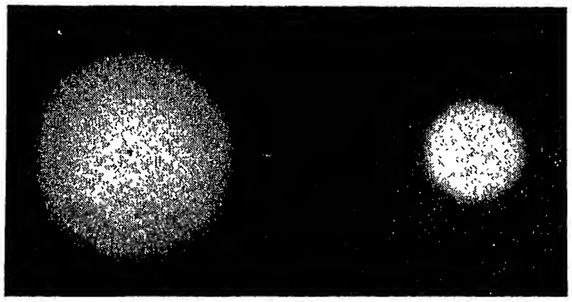

FIG. 3—LICHTENBERG FIGURES

The initial step in the sparkover process
Air pressure: 16 cm. Hg.
Field: S, 5,150 lines per cm.^{2}
Electrodes spaced 10.2 cm.

of a sphere spark-gap, diameter of spheres 10 in. (25.4 cm.). For Figs. 8 and 9 the impulse energy was increased by placing a glass-tinfoil condenser of $3.6 \cdot 10^{-3}$ μ f. capacitance in parallel with the spark gap. Cathode-ray oscillograms of the voltage impulse showed a very steep wave front, the voltage reaching peak value in approximately two and a half microseconds.

The direction of the magnetic field with respect to the

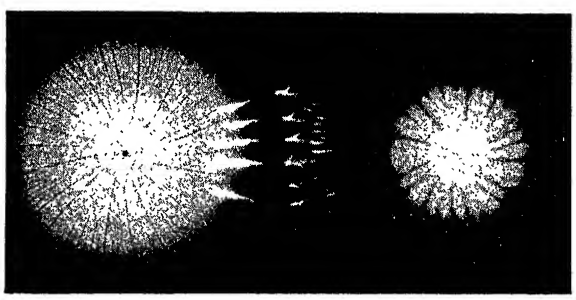

FIG. 4—LICHTENBERG FIGURES

Suppressed sparkover
Air pressure: 13.4 cm. Hg.
Field: S, 5,060 lines per cm.^{2}
Electrodes spaced 10.2 m.

emulsion surface of the photographic plate is indicated by the letters N and S. If the north pole was in front and the south pole behind the printed figure (reverse of photographic plate) the direction is marked N. The letter S indicates the reverse direction. The flux density is given lines per cm.^{2} of field-pole surface.

In a preceding paper[13] evidence is presented on the formation process of Lichtenberg figures. The deflections of the streamers in the positive as well as in the negative figures, when formed under stress of a strong magnetic field, show that electrons, and not positive ions or protons, are the active elements at *both electrodes*.

That the positive figures are formed by electrons falling into the positive electrode is likewise the conclusion reached by Marx (*loc. cit.* page 68) on the basis of results obtained from an ingeniously devised experiment.

In essence the formation process may be described as follows:

For the negative figures the electrons are projected at high velocity, away from the negative electrode, forming spreading streamers, due to the mutual repulsion existing between the projected electrons in each

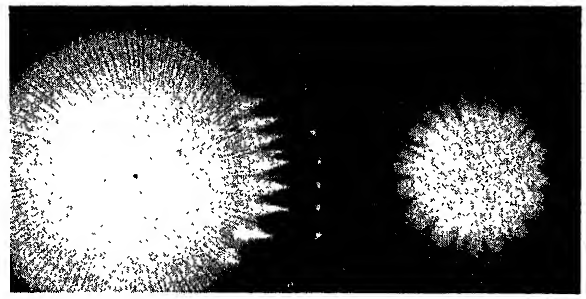

FIG. 5—LICHTENBERG FIGURES

Suppressed sparkover
Air pressure: 12.5 cm. Hg.
Field: S, 5,100 lines per cm.^{2}
Electrodes spaced 10.2 cm.

streamer. The bending of the streamers from the negative electrode in Figs. 3, 4, and 5 is in accord with this statement.

For the positive figures electrons are likewise the active elements but the process is fundamentally different. At the positive electrode the electrons are attracted towards and fall into the positive electrode instead of being repelled and projected away, as at the negative terminal. The locus of the potential gradient wave of the impressed impulse spreads outwards from the posi-

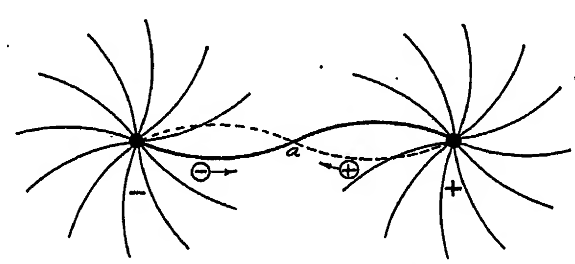

FIG. 6—DEFLECTION OF SPARKOVER PATH PRODUCED BY MAGNETIC FIELD OF S DIRECTION

tive electrode and, if the gradient be greater than necessary to produce ionization, streams or slides of electrons, produced by secondary ionization, fall into the positive electrode.

The grooves or channels forming the positive figures are assumed to be paths of low resistance during the inrush of the electrons, with the voltage gradient at the tip of the streamers providing the initiating ionization. These sources of the electron streams rapidly

progress outwards from the positive electrode until the voltage gradient for any streamer tip becomes less than the ionizing potential. At the instant the initiating ionization at the tip of the groove ceases, the electron stream in that streamer collapses and the cycle for the formation of the positive figure is completed. If the voltage gradient at the electrode continues above the ionizing potential, or recurs, the cycle repeats as in the case of corona, brush discharges, etc. The streamers in each cycle extend outwards with the radial distances approximately proportional to the respective potentials.

At atmospheric pressure the bending of the negative and positive streamers by the magnetic field is very

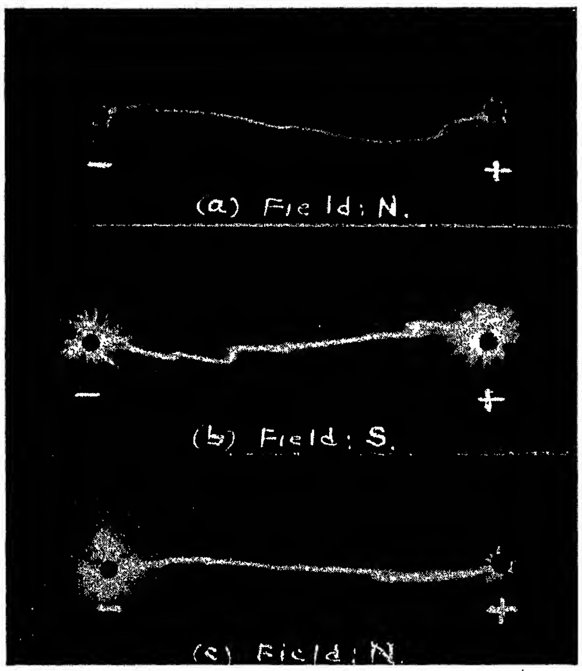

FIG. 7—THREE SPARKOVER PATHS

Air pressure: 15 cm. Hg.
Field: 12,500 lines per cm.²
Electrodes spaced 5 cm.

small. By decreasing the air pressure in the plate-holder the deflections produced by the magnetic field become proportionately larger. For pressures less[13] than 3 cm. Hg. the appearance of both the negative and positive Lichtenberg figures becomes strikingly different, when produced under the stress of magnetic fields, from those obtained under atmospheric pressure conditions. While the bending of the streamers in Figs. 3, 4, and 5 is not large, it is ample to show that the moving elements must be negatively charged bodies, that is, electrons and not positive ions for both the positive and the negative figures.

(a) *The active elements in kindling mechanism.*

A graphical representation of the path followed by an electron, under the combined stress of dielectric and magnetic fields in space quadrature, in passing in a gas from the negative electrode through the middle point a to the positive electrode is shown in Fig. 6. The magnetic field direction is S, that is, the south pole is above and the north pole under the printed page. Hence the reaction of the magnetic field on electrons projected radially from the negative electrode causes a deflection in the counter-clockwise direction around the negative electrode as center of reference.

Consider an *electron projected from the negative electrode* under the given conditions and passing through the point a midway between the two electrodes. The electrostatic force of repulsion from the negative electrode and attraction to the positive electrode combined with the reaction from the magnetic field, at right angles to the direction of motion, will cause the electron to move along the path indicated by the full line in Fig. 6. It is evident that under the action of the magnetic field the paths of all *electrons falling into the positive electrode* will move in paths bending in the counter-clockwise direction, with reference to the positive electrode, as indicated in Fig. 6. Hence, if electrons be the active elements in the sparkover process the path followed by the spark should have a double inflection as illustrated by the full line in Fig. 6. On the other hand, if *positive ions or protons be the active elements* in the sparkover mechanism the path followed by the spark should likewise have a double inflection, but must be curved in the reverse direction, as indicated by the broken line in Fig. 6. *The deflections of the sparkover path therefore can be used as a criterion in determining whether electrons or positive ions or protons are the active elements in the sparkover process.*

On this basis consider the three sparkovers recorded in (a), (b), and (c), Fig. 7. In (b) the field direction was S, the same as used for the diagram in Fig. 6. The sparkover path has a double deflection like that of the full line curve in Fig. 6. In Fig. 7 (a) and (c) the direction of the field is N, that is, reversed as compared to the direction in (b). The deflection of the sparkover paths in (a) and in (c) are also reversed as compared to (b). It is therefore evident that the photographic records of the sparkovers in Fig. 7 tend to prove that electrons, and not positive ions or protons, were in each case the active elements in the kindling stage of the sparkover process.

By reducing the pressure of the air surrounding the photographic plate the bending effect of the magnetic field is proportionately increased. A series of photographs of sparkovers was taken at air pressures ranging from atmospheric to 0.02 mm. Hg. Typical results illustrating the kindling stage of the sparkover process at reduced air pressures are shown in Figs. 8 to 13 inclusive. Unfortunately it is not possible to reproduce on the printed page by means of half-tone cuts much of what appears on the photographic plate. Even the photographic prints are in many respects inferior to the original plates.

In the series of photographs from which Figs. 8 to 13 were selected the spacing of the electrons was kept constant at 10.2 cm., and the impressed voltage adjusted so as to record on the photographic plate the kindling stage of sparkover formation. The deviation of the sparkover path from a straight line increases with decreasing air pressure. The double inflection of the curve, in each case, follows the path that would be taken by negative charges, that is, electrons, as illustrated by the full line in Fig. 6. It therefore appears from the photographic records, under the given limitations of the experiments, that during the kindling stage and until actual sparkover has occurred, electrons and not positive ions or protons are primarily the active elements in the sparkover mechanism.

FIG. 8—SPARKOVER SUPERIMPOSED ON LICHTENBERG FIGURES

Air pressure: 9.9 cm. Hg.
Field: N, 5,050 lines per cm.^{2}
Electrodes spaced 10.2 cm.

FIG. 9—INCIPIENT SPARKOVER

Air pressure: 1.8 cm.
Field: N, 5,200 lines per cm.^{2}
Electrodes spaced 10.2 cm.

FIG. 10—SPARKOVER IN THE MAKING

Air pressure: 0.15 cm. Hg.
Field: S, 5,200 lines per cm.^{2}
Electrodes spaced 10.2 cm.

At low air pressures[13] the negative Lichtenberg figure develops grooves or channels as illustrated in Fig. 13, markedly different from the fan-shaped sectors of uniform texture at higher pressures, as in Figs. 3, 4, and 5 or for those taken under atmospheric pressure. The bending of the rays when the figures are taken under the stress of the magnetic field shows that at all pressures electrons, projected from the negative electrode, are the active elements in the formation of the negative figure. At air pressure less than 3 cm. Hg. the appearance of the positive figure changes into a nebulous form lacking definite structure. The sweep of the nebulous positive figure when formed under the stress of the magnetic field, as in Fig. 13, clearly indicates that the active elements during the kindling stage of the sparkover process are electrons falling into the positive electrode. The double inflection of the sparkover path in Fig. 13, arrested before complete sparkover occurred, is very marked, and in accord with

FIG. 11—SPARKOVER IN THE KINDLING STAGE

Air pressure: 0.13 cm. Hg.
Field: S, 5,150 lines per cm.^{2}
Electrodes spaced 10.2 cm.

FIG. 12—SPARKOVER IN THE KINDLING STAGE

Air pressure: 0.07 cm. Hg.
Field: S, 5,100 lines per cm.^{2}
Electrodes spaced 10.2 cm.

the analysis of the path that would be followed by electrons, indicated by the full line in Fig. 6. There is no evidence in Fig. 13 or on any of the photographic plates of a counter flow of positive ions or protons.

(b) *Lichtenberg figures and the sparkover process.*

Although the number and range of experiments made on Lichtenberg figures and sparkovers formed under stress of the magnetic field are limited, the results obtained, combined with the many important relations previously known in regard to Lichtenberg figures and other forms of electric discharges, may warrant the following observations on the interdependence of Lichtenberg figures, electric sparks, and the sparkover process.

1. Lichtenberg figures represent, or are formed by, elementary electric sparks. On this basis the process of formation of the Lichtenberg figures would also represent the kindling mechanism of the simplest form of electric sparks.

2. Lichtenberg figures, or the electric sparks producing them, form the initial step in the sparkover process. Preceding the sparkover proper, comes "der dunkle entladungs vorström"[11] which, in a way, corresponds to the darts and streamers in Torok's "suppressed discharges,"[3] that is, a rapid succession of Lichtenberg figures forming cycles.

At the *negative electrode,* electrons are projected away at high velocity which with ionization by collision produce the negative figure. As a consequence a negative space charge is formed near the periphery of the negative figure and a positive space charge near the negative electrode.

At the *positive electrode,* as the voltage gradient becomes greater than the ionizing potential, positive streamers or slides suddenly develop and collapse forming the positive figure. For increasing impressed voltage each succeeding set of streamers extends further towards the negative electrode than the one preceding.

3. Sparkover develops from the tips of the positive Lichtenberg figures.

When a positive streamer extends near to the negative figure a rapid increase occurs, as illustrated in Figs. 3, 4, and 5, probably due to the excess of electrons forming the negative space charge at the periphery of the negative figure. If the impressed voltage be sufficiently high, the voltage gradient at the tip of the positive streamers extends the path of low resistance thereby bridging the gap to the negative electrode. This forms the initial conducting sparkover path which rapidly develops into the full sparkover channel, as illustrated by Figs. 7 and 8. The initial sparkover channel, Figs. 7 and 8, apparently follows the positive and negative streamers with sharp turns when changing from one streamer to the next. It seems quite evident that zigzag channels, as shown in Figs. 7 and 8, could not be formed by elements projected from the negative electrode; but could well be developed by electrons falling into the positive electrode; the formation process starting at the positive electrode and extending along the streamers to the negative electrode.

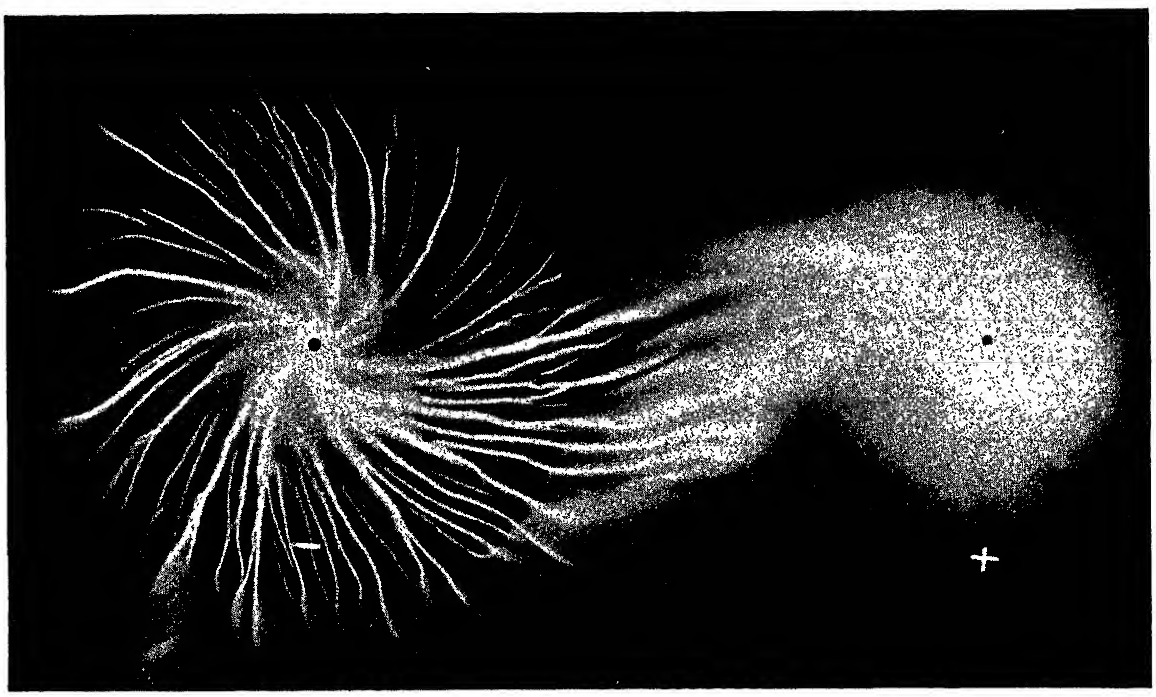

FIG. 13—ARRESTED SPARKOVER

Air pressure: 1.3 cm. Hg.
Field: S, 5,160 lines per cm.[2]
Electrodes spaced 10.2 cm.
1 megohm resistance in series with spark-gap

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Discussion

Hugh Skilling: In support of Professor Magnusson's three conclusions I am pleased to mention a study in the Ryan Laboratory last winter. That work led to very similar conclusions. The following is quoted from a report to Dr. Ryan concerning superposed 60-cycle and impulse phenomena between points.

"Contrary to expectation, experiment has shown that the existence of 60-cycle corona between points has very little influence on the phenomena exhibited by the gap when an impulse voltage is applied.

"Arrested discharges of impulses of voltage were observed, measured, and photographed between points; then without changing any other condition of the circuit, a 60-cycle voltage was applied between the points and at the moment of maximum 60-cycle voltage an impulse was thrown on and arrested. Except in slight details, the action of the impulse was unchanged." The 60-cycle voltage applied was 95 per cent of 60-cycle breakdown voltage, and gave profuse corona.

This work, combined with previous knowledge, requires a modification of accepted theory.

"When 60-cycle voltage is applied between points, it rises gradually in each half-cycle until corona commences. At once, space charge becomes the controlling factor in limiting ionization. But at all times of profuse ionization there are many electrons traveling rapidly toward the positive electrode; these are magnetically drawn together into luminous streamers of high conductivity. The cause of the intense ionization that must take place in these streamers is not definitely known, but there are several contributing factors. For instance, energy lost in the streamer will appear as heat, and as the air becomes warmer the mean free paths become greater, ionization more intense, and more heat will appear. As the mean free path becomes quite long, complete ionization of the air in the streamer may be approached. At any rate, ionization is copious enough to maintain the streamer as space charge reduces the voltage gradient from thirty to six kilovolts per centimeter; an intense space charge of positive ions will be formed at the head of the streamer as electrons are carried away, and although this will lower the voltage gradient of the streamer behind it, it will so increase the gradient ahead of the streamer that the streamer will grow longer and by this process extend itself. It will grow out from the positive point until the available voltage is largely consumed by voltage drop along the streamer. When the gradient just beyond the head of the streamer is no longer great enough to supply a large current to the streamer, its consumption of voltage per inch rises, and the current falls even more—dropping suddenly to zero and extinguishing the streamer. But in case the streamer should reach to the negative space charge that has in the meantime been deposited about the negative point, its current will be increased and in most cases it will grow to the negative electrode and so result in complete breakdown of the gap.

"After one streamer has shot out from the positive electrode, the space through which it has penetrated is filled with positive ions, and a dispersion of these is necessary before another streamer can enter the same region. There is a tendency for these positive ions to shield all routes by which streamers might issue from the positive point. Hence, it is only during a small fraction of the total time that a streamer is in actual existence and during the remaining time the electric field between the points is very little different from that which would exist in the absence of streamers. Diffuse corona is the superposition of the thousands or millions of streamers that project themselves each second, while individual filaments bright enough to be distinguished probably have a longer life.

"It is only occasionally that a streamer issues in a similar manner from the negative electrode. Presumably a higher electric field is needed to maintain such a negative streamer, and it is more intense in every way when by chance it is formed. A field-strength greater than 30 kilovolts per centimeter is a commonplace in impulse phenomena, and negative streamers are evident in every arrested discharge, but at 60 cycles it is only by chance that such a streamer may start, and even in the most violent corona they are only seen a few times in a cycle. This is not improbably due to the fact that at the positive electrode, all electrons formed in the corona will converge toward the point, while the only electrons near the negative point are the few produced near it and diverging from it.

"The chief evidence favoring this theory is found in the experiment just described, and in the well known but unexplained relationship of 10 kilovolts per inch for breakdown between electrodes of any shape if corona precedes flashover. The nature of oscillograms of corona current—showing many small positive streamers and few but vigorous negative ones—is explained, and so are many of the characteristics of asymmetrical electrodes such as the case of flashover from point to plane coming always with the point positive."

Moreover, this work agrees very well with Professor Magnusson's results. The additional proposition of the discontinuity of electric discharge seems to make more clear the action in several of Magnusson's excellent figures.

S. S. Mackeown: Some twenty years ago Townsend derived theoretically the conditions necessary to obtain a spark discharge and was able to check his results experimentally over a rather wide range of conditions. He showed that it was essential to have positive ions produce ionization as well as the electrons. Although the positive ions produce a small amount of the ionization compared to the electrons, this ionization is essential for the spark discharge.

The mechanism of the spark discharge seemed to be satisfactorily explained until a few years ago when Rogowski and others found that the time necessary for a spark discharge to occur was of the order of 10^{-8} seconds. Now a spark will occur between plane parallel plates when the field exceeds approximately 30 kilovolts per centimeter. However, it is known that an electron cannot cause ionization in a gas until it has acquired a perfectly definite amount of energy. In air this corresponds to the energy acquired when the electron falls through a potential of about 18 volts. On the average every time an electron hits a gas molecule it loses its energy in the forward direction, and the average energy that an electron will have when it hits a gas molecule is the product of its mean free path and the electric field. The mean free path of an electron in air is approximately 4×10^{-6} cm., so if the electrons are to hit gas molecules with an average energy corresponding to 18 volts, there must be an electric field of some 5×10^{6} volts per cm. However, it is not the average electron which is important in producing a discharge but those few which have acquired high velocities due to either having traveled a distance large compared to the mean free path without making a collision or else due to the fact that they have not lost all of their forward momentum at the last collision. It is difficult to see how there could be an appreciable number of electrons having an energy greater than 10 times the average. If then we assume that the discharge is produced by electrons having energy 10 times as great as the average, we would expect a discharge to occur when the field was approximately 5×10^{5} volts per cm., which is more than 10 times greater than that at which it does occur. The fact that a spark occurs in 10^{-8} seconds indicates that the field must be distorted so that at some place it has a value of 10 times the average and that this distortion occurs in 10^{-8} seconds. Slepian has gotten around this difficulty by assuming thermal ionization, which, however, for several reasons is not acceptable. Hippel and Franck as well as Loeb assume that this distortion is produced by an initial flow of electrons which distort the field, but their theories are not completely satisfactory. If we assume that this distortion of the field does exist, then Townsend's theory is satisfactory to explain the occurrence of a spark. Consequently, the interesting part of the spark discharge is what occurs in the first 10^{-8} seconds.

Professor Magnusson's pictures were produced with a voltage wave which reached a maximum in 2.5×10^{-6} seconds and the pictures are a record of what occurred in probably 10^{-5} seconds. This is 1,000 times the length of time necessary for the sparkover to occur. Unfortunately there does not seem to be any way to determine the sequence of events in this period of time. As far as the pictures go it is perfectly possible that ionization occurred first at the anode and later at the cathode, or *vice versa*, or that they occurred simultaneously. It would, therefore, seem dangerous to draw conclusions regarding the actual formation of a spark from the data present in this paper.

I would like to reiterate again that while the greatest part of the ionization is due to electrons, yet ionization by positive ions is essential and no spark can occur unless both types of ionization are present.

H. G. Cordes: The statements (a) and (c) of Professor Magnusson's paper and the theory deduced from the figures appear to require critical examination. Consideration of either mean free path or space charge invalidates the theory illustrated by Fig. 6. The mean free path of an atom in air at atmospheric pressure is of the order of 10^{-5} cm. and at 0.07 cm. Hg. pressure it is 10^{-2} cm. Although the mean free path of an electron is longer than that of a positive ion, the separation of electrons and ions is too small for observation by inspecting an illustration hence they cannot follow the widely separated paths shown by Fig. 6. Electrons may be the principal charge carriers due to their small size and high velocity but enough positive ions are formed by collisions to reduce the space charge to practically zero.

Reference to Fig. 7 does not seem to sustain the theory because both the positive and the negative streamers are recorded on the emulsion before a spark passes directly between the electrodes. In other words the streamers are ionized paths produced by displacement current flowing through the copper plate and a spark directly between the electrodes is initiated by a relatively short spark from the tip of a negative to the tip of a positive streamer. The short spark took place in Fig. 7A at a point below a straight line between the electrodes whereas in Fig. 8 it passed above the line; this indicates that preliminary ionization of the streamers rather than the blow-out effect of the magnetic field determines the location of the short spark. If this explanation is correct, omission of the copper plate should result in the spark always taking place on the same side of the straight line and in requiring a higher potential to initiate the spark while the pressure and field, of course, remain the same.

The streamers recorded by the emulsion on the photographic plate are probably produced in steps even when a potential of *very steep wave front* is impressed on the electrodes. The presence of grooves at low pressures shows that the record is made by the heat of the discharge instead of by actinic rays; the resulting emulsion vapor is an unknown factor with respect to pressure and composition.

The presence of canal rays in a continuous, but otherwise similar, discharge indicates that positive ions are a component of a spark discharge; pure electron discharges, which take place without this component, have been produced only in very highly rarefied spaces.

C. E. Magnusson: It is indeed gratifying that Dr. Skilling's experiments made in the Ryan Laboratory, "led to very similar conclusions" although the experimental conditions were as widely different as may well be obtained.

In reply to Dr. Mackeown's assertion that "ionization by positive ions is essential and no spark can occur unless both types of ionization are present," let me refer to an important contribution recently made by Rogowski,* in which he reaffirms his earlier contention that for impulse sparkover the positive ions do not play the role ascribed to them by Townsend's theory. He shows that for short time impulses, 10^{-5} sec. or less, the positive ions are essentially stationary.†

In regard to Mr. Cordes' question let me state that with both electrodes in contact with the emulsion surface (Fig. 1) the bending of the rays and the double inflection of the sparkover path are in the same direction whether a metal plate is in the plate-holder or not. The presence of the metal plate aids in producing more sharply defined figures, especially at low air pressures, but does not affect the direction of the bending of either the positive or the negative streamers or the double inflection of the sparkover path.

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Radio Coordination

BY C. C. CAMPBELL* and H. N. KALB†
Associate, A. I. E. E. Non-member

Introduction

THIS paper is written from the authors' experience with radio interference problems in northern and central California. An attempt has been made to present the various phases of the problem and their relation to each other rather than an extensive presentation or solution of any particular phase. The application of mathematical theory for the solution of radio interference problems is in many ways highly complex. Fundamental formulas are used only to present the material more clearly.

Radio interference from natural static and radio sources is not within the scope of this paper and is mentioned only in so far as it has a bearing upon interference caused by electrical sources. Natural static is less severe in the West than in the East, making other types of radio interference more apparent. A larger network of higher voltage lines has been built up in the West because of the extensive hydroelectric development and a more scattered population and this fact also alters the problem to some extent.

The variation of broadcast service area due to power and location and the topography of the surrounding country have an important bearing upon the radio interference problem. The problem will require different treatments depending upon the broadcast coverage in different sections of the country.

History and Development

During the past decade, broadcasting for entertainment and other purposes has grown from a small unimportant industry to one of major importance. The broadcast of scheduled programs for the public really began in the latter part of 1922. In 1923, a few complaints of radio interference were received by the power companies, doubtless, because they are depended upon to a great extent to help their customers in various electrical problems. The power companies with little to draw from by way of a background of experience or research in this field, met the problem with a spirit of cooperation and helpfulness toward the broadcast listener and the radio trade.

The first interference investigations revealed a great number of home-made receivers, many of which were of the single-circuit regenerative type. These home-made receivers had many loose connections and run-down batteries, which accounted for a large percentage of the radio interference complaints at that time. The average broadcast listener did not complain about poor quality of reception or a small amount of noise. He did not protest unless the interference was serious enough to make reception from most broadcast stations impossible. As the radio industry grew, the tone quality of radio transmitters and receiving sets was improved and listeners took more interest in obtaining good reception. Battery receiving sets were used and listeners found they could purchase fairly satisfactory manufactured sets at a reasonable price. Interference due to poorly constructed radio receivers and regenerative receiving sets was reduced. It soon was found that considerable interference originated in industrial and household electrical devices, utilities' lines, and in other miscellaneous electrical and radio sources. Interference was picked up by battery supplied receivers by direct induction in the antenna-ground system and only the more severe cases of interference were found troublesome.

The next important change was from battery-operated receivers to receiving sets supplied directly from the a-c. lighting lines. Battery eliminators coupled receivers conductively to the lines, and noises not previously noticed were brought in and resulted in an increase in the number of complaints received. An increase in the number of interference complaints was also caused because radio was a considerable novelty and listeners attempted to get low powered distant stations and were often very successful. The next change included the radio power supply as part of the receiver and this change further increased the coupling between the power supply lines and the radio receiver itself. The modern radio receiver, made in a single unit, has excellent tone quality, satisfactory selectivity and high sensitivity. Some of the later superheterodyne receivers have a sensitivity of less than one microvolt per meter. With the excellent programs now broadcast and the desire of the radio listeners for clear reception, interference complaints have increased. They have also increased because of the greater number of receivers in use and because keen radio retail competition is pressing radio sales in noisy locations and in places remote from broadcasting stations.

During 1926, after the breakdown of the 1913 radio act, broadcasting stations sprang up almost overnight. Considerable interstation heterodyne interference developed. The present Federal Radio Commission (created by the radio act of 1927) held its first meeting on March 15, 1927. Order in broadcasting was brought about by relicensing all stations, reassigning frequencies and power. On the Pacific Coast, heterodyne interference is a minor factor at the present time. The present trend toward the superheterodyne receivers will allow higher power in broadcasting without

*Pacific Gas and Electric Co., San Francisco, California.
†San Joaquin Light and Power Corp., Fresno, California.

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seriously increasing heterodyne interference. Interference from radio sources is not within the scope of this paper and is mentioned only because at this time many interference complaints received by the power companies were found due to this cause.

Fig. 1 shows the total number of receivers sold including consoles, midgets, and radio-phonograph

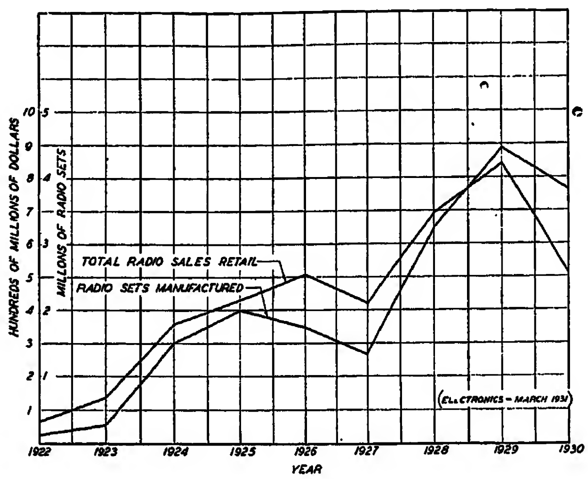


FIG. 1—NUMBER AND VALUE OF RECEIVING SETS SOLD IN THE UNITED STATES 1922-1930

combinations. The number of receivers manufactured has increased from 100,000 in 1922 to 4,438,000 in 1929. The curve of values includes the amount of sales in dollars of all receivers, tubes, parts, and accessories. The retail value of radio sales increased from $60,000,000 in 1922 to $842,548,000 in 1929. The average selling price of a radio receiver has varied from $50.00 in 1922 to $127.00 in 1927. Since the latter year, the price has dropped gradually and in 1930 it was $82.00. The average retail unit price of tubes has decreased from $6.00 in 1922 to $2.30 in 1930. Of the 30,000,000 receivers now in use in the world, approximately 50 per cent or 15,000,000 are operated in the United States.[3]

ADVANTAGES OF RADIO INTERFERENCE INVESTIGATIONS

The advantages of radio interference investigations to all branches of the radio trade and to the radio listeners are many and obvious. The elimination of radio interference under the present system of broadcasting is of considerable value to the individual broadcast stations in permitting them to reach a greater audience with their programs.

In radio the power company has a very desirable load, as it yields a higher revenue per kilowatt of demand than most other electrical appliances. The connected radio load in the United States is estimated at 1,500,000 kilowatts and on the basis of 4 hours daily use and $0.05 per kilowatt hour, this means an approximate revenue of $100,000,000 per year. Extra heating and lighting also account for an appreciable increase in revenue. Some companies are now making regular use of radio to patrol their lines. Perhaps the most important advantage of interference investigations is the customer good-will building possibilities.

3. For references see Bibliography.

RESPONSIBILITY

Table I shows the number of complaints investigated yearly by the Pacific Gas and Electric Company from 1924 to 1930. The complaints investigated by agencies other than the company itself are not included. The increase in the percentages chargeable to the power company in 1928, 1929, and 1930 was due to several causes. The first and perhaps the most important was the large number of a-c. receivers sold since 1928. Alternating current receivers being conductively coupled to the supply lines makes them more susceptible to line noises. Radio trade association's investigations also started in 1928 and since they only cover metropolitan areas where the percentages of complaints due to power companies are the least, the omission of these complaints in the table also accounts for the increasing percentages shown since 1928.

TABLE I

Year	Number investigated by P. G. & E.	Per cent due to P. G. & E. Co.	Per cent due to other causes	Per cent cleared themselves
1924	90	30.0	37.5	32.5
1925	469	45.0	33.0	22.0
1926	1,782	30.0	40.5	29.5
1927	2,384	31.8	47.7	20.5
1928	2,973	36.6	40.6	22.8
1929	3,479	50.0	33.1	16.9
1930	3,736	51.5	32.4	16.1
Total	14,913	42.2	37.7	20.1

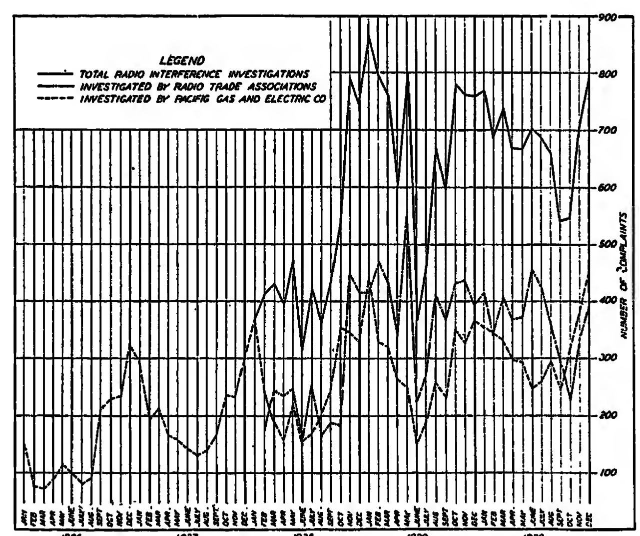


FIG. 2—RADIO INTERFERENCE COMPLAINTS INVESTIGATED BY THE PACIFIC GAS AND ELECTRIC COMPANY 1926-1930

The increase in the number of complaints shown in Fig. 2 is due to the increased number of radio receivers sold and in use, the increased sensitivity of the receivers, the publicity given radio interference investigations by

radio trade associations, and a greater desire on the part of the radio listening public for programs free from interference.

The curve shows a definite seasonal trend, the peaks usually occurring during December or January. The increase during the winter months may be accounted for to some extent by the larger number of receivers sold at this time of year, especially at Christmas. People remain at home more during the winter months and spend more time listening to the radio programs. Many noises heard in the summer time are charged to natural summer static and no complaint is made. There is a tendency for the curve to flatten out more each year during the summer months showing people are spending more time than formerly listening to the summer broadcasting.

Any interference producing device connected to the electric power supply network, for which utilities cannot be held responsible and over which the utility has no control, feeds radio frequency disturbances over a considerable portion of the utilities' circuits. This is the responsibility of the appliance manufacturer and not that of the individual owner. In most cases the latter buys and operates such a device without knowledge of its causing interference.

The responsibility for improper or inadequate installations and for defective radio apparatus rests directly with the radio trade. The public's responsibility is doing business with a reputable radio dealer and cooperating with the interference investigator.

Cooperation

There ought to be close cooperation between parties responsible for radio interference in order that the best possible public service may be given in the most economical manner.

Cooperative radio interference investigations have proved valuable in metropolitan areas where the general noise level is caused by a large number and variety of electrical devices. This is true to a greater degree in congested areas than in the less populated areas. Cooperative investigations usually are conducted by a radio trade association. The radio trade association can take the part of a neutral and unbiased party, locate sources of interference, regardless of its source, and properly place the responsibility. Under such a plan the power company, of course, loses its identity in the matter, which may or may not be to its advantage. Cooperative investigations have been carried on successfully in some parts of California for the past three years (1928-1930).

Coverage of Broadcast Stations

"Fair service broadcasting is roughly estimated by some at one mile for a 5-watt station, ten miles for a 500-watt station and one hundred miles for a 50,000 watt station, but 5 watts may be heard 1,000 miles on a winter night and any amount of power will usually fade at 100 miles, all of which causes confusion and misunderstanding on the part of the uninitiated."

"Reliable service means good reception at all hours of the day and night throughout the year under the most favorable interference conditions. With interference present, the distances will be greatly reduced."[1]

It must be remembered that from an interference standpoint the quality of reception is dependent on the ratio of modulated field strength to noise level. Various writers have suggested values for this ratio varying from 15 to 150. If 80 per cent modulation of the broadcast wave and a noise of 30 microvolts per meter is assumed, the field strength required to overcome the noise would be from 565 to 5,650 microvolts per meter. If the ratio is assumed to be 100, then a field strength of 3,750 microvolts per meter would be required. With these assumptions and the present power and location of broadcast stations in the west, only a small percentage of the area can be receiving fair broadcast reception.

In the San Joaquin Valley there is only one broadcasting station (100 watts) and that station (K. M. J.) is located at Fresno. The larger stations are located at San Francisco and Los Angeles at an average distance of approximately 160 miles and 200 miles respectively from Fresno, and in both cases separated from the valley by mountain ranges. A broadcast field strength survey of this valley was made in the middle of November 1930, readings being taken at seven different cities scattered throughout the entire length a distance of approximately 180 miles. The Pacific Telephone and Telegraph Company had made similar readings at two of the same locations in the month of September. From these readings a curve was made to show what field strength could be expected throughout the valley, if the whole survey had been made in September. Such curves for the largest San Francisco and Los Angeles stations are shown in Fig. 3. It should be noted that the rated power of K. P. O. is 5,000 watts as against 1,000 for K. F. R. C. However, there is not a 5 to 1 ratio between their field strengths, but this ratio continues to become smaller as the distance from the broadcasting stations increases. The average field strength at Fresno of all the stations shown is approximately 130 microvolts per meter. If the power of these stations were increased to ten times the present, this average field strength would then probably be something less than 400 microvolts per meter, which would not give a sufficient ratio between signal and noise to provide coverage of this area. This is not peculiar to the San Joaquin Valley, but applies to all other sections distant from the two broadcasting centers, *i. e.*, San Francisco and Los Angeles.

Therefore, it will be seen that there is a need for better broadcast coverage in California. Table II shows the airline distances from the San Francisco area, where the most powerful northern California broadcast stations are located, to some of the larger

cities in northern and central California. A similar condition prevails in southern California, Oregon, Washington and Nevada.

TABLE II

City	Airline distance from San Francisco
San Jose	40 miles
Stockton	65 "
Sacramento	75 "
Salinas	85 "
Auburn	100 "
Marysville	100 "
Chico	140 "
Fresno	160 "
Red Bluff	170 "
Redding	200 "
Eureka	233 "

"The rural listener of the west also has little choice of programs, due to the fact that radio stations in the fifth zone, which embraces two-fifths of the area of the United States, have been allocated only 65,000 watts power, while the stations in the other zones have power aggregating 525,000 watts. Perhaps too much thought has been given to population and not enough to area in the allocation of power and frequencies."[2]

The steady flow of current as in an arc light or rectifier tube under normal operating conditions will not cause serious interference. The air remains completely ionized and becomes a good conductor. A spark causing high-frequency currents may or may not be necessary for the normal operation of the apparatus. The high-frequency currents are either directly radiated by the circuit in which the spark takes place or are transferred to another closely coupled circuit from which radiation takes place. When free to oscillate, the circuit in which the spark takes place and all coupled circuits oscillate at all frequencies in which the inductive reactance is equal or nearly equal to the capacitive reactance.

$$\text{If } R > 2\sqrt{L/C} \text{ No oscillation}$$

$$\text{If } R < 2\sqrt{L/C} \text{ Oscillation}$$

The resistance of power circuits is generally low and therefore usually will oscillate in resonant parts or throughout when excited by a spark discharge.

Interference originating on a 60-cycle primary circuit (2,300 to 25,000 volts) has in most cases a characteristic sound. The gap producing the interference breaks down near the peak of each half of the 60-cycle voltage wave and sets up damped high-frequency wave trains.

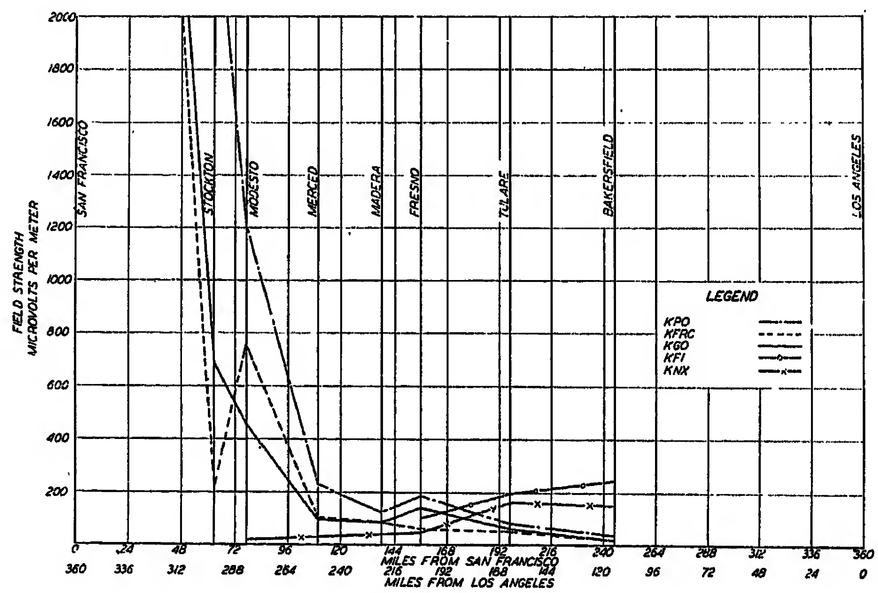


Fig. 3—Field Strength of Broadcasting Stations

Sources of Interference

For analytical purposes, any source of radio interference may be referred to as the influence; the ability of the receiving set to pick up and reproduce the interference, the susceptiveness; and the resistance of the path between the influence and the receiving set as the coupling factor.

In general, any spark which causes a rapid change in current flow or the sudden discharge of a stored electrostatic field will generate radio frequency currents. This excites the circuit 120 times per second on a 60-cycle system and the radiated wave produces 120 vibrations in the telephone headset or loudspeaker. Interference from the higher voltage lines (25,000 volts and up) may best be described as a "roar." This is due to numerous individual sources of interference differing in magnitude and occurring at different times.

Interference from appliances connected to service lines has a different sound than the above mentioned cases, although supplied from a 60-cycle source of

power. These sounds may best be described as mechanical. Examples of this type of interference are vibrating devices, thermostatically controlled appliances, brush motors, etc. It is very difficult to describe sound in a satisfactory manner but an interference investigator learns the different types by experience. Interference originating on the low-voltage side of a distribution transformer usually causes trouble only to radio listeners supplied from this transformer or for a short distance on the high-voltage line side.

At one time amateurs were blamed for considerable interference but have proved their innocence to a great extent. Furthermore they have shown a friendly spirit of cooperation in the elimination of interference.

An attempt to list completely all sources of radio interference would result in repetition as far as fundamental causes are concerned. Sources of interference may, however, be divided into the following general groups:

1. Utilities.
   1. Electric power and light companies.
   2. Electric Railway companies.
   3. Communication companies.
2. Industrial and Domestic Electrical Apparatus.

Electric Light and Power Companies

Transmission Lines—30,000 volts and higher.

1. *Brush discharge from conductor.* This is not of major importance at present. It is due principally to roughness of the surface of the conductor.

2. *Suspension type insulators.* This is not of major importance at present. The discharge comes from the gap between the metal cap and porcelain, and around the pin at the point of contact with the cement.

The remedy is to provide sufficient clearance between cap and porcelain or fill the gap with a compound that will remain slightly plastic and will not crack. At the pin the metal should have no sharp edges or points and the cement should be smooth and even with the porcelain surface. Additional units can be used to keep the voltage across any unit below the critical interference voltage. If it is necessary to use corona shields, they should be placed so as not to allow a brush discharge to the porcelain.

3. *Bushings—Switch and Transformer.* Oil-filled or compound-filled bushings should give no trouble except in the possible case of potential transformer bushings where a pin connection is sometimes made. This connection should be made more positive as the oxidation on the pin causes a discharge to take place. Bushings with air columns for conductor space may be lined with metal if a close contact is made between the metal lining and the porcelain. If the conductor can be made a part of the bushing, the hole may be filled with metal filings of non-magnetic material, or with oil. If the conductor is to be removable, a split brass sleeve will answer fairly well. Copper plating, if properly done, provides a very good result. Copper wire screen may be used with good results provided it is well covered with an insulating varnish. In all cases the metal must at some point make good contact with the conductor. Bushings to be used in connection with bushing-type current transformers should have a copper-plated surface from the supporting flange to a point over the cement ring joining the lower part of the outer porcelain tube and the adjacent tube. This acts as a static shield.

4. *Pin Type Insulators.* There are several possible sources of radio interference involving pin type insulators. A great amount of work has been done to develop a new insulator that will not produce interference, by metallic glaze, coating, etc. Inexpensive methods of treating insulators now in service would help the situation.

5. *Bond wires and hardware on wood pole construction.* Bond wires should always be placed between double nuts and never next to the wood. Hardware should be so spaced as not to allow discharges, or it should be well bonded.

Distribution Lines—5,000 Volts to 30,000 Volts.

1. *Hardware discharges.* This can be cared for by changes in construction standards which provide for either greater separation or proper bonding.

2. *Air switches.* Switches now in use can be bonded by the operating companies, and those being manufactured can be provided with proper bonds by the manufacturers. Where iron caps are cemented to the tops of insulators in the making of these switches, sufficient clearance should be allowed between the lower edge of the iron cap and the porcelain.

3. *Transformers.* Interference from distribution transformers is due to several causes and is corrected in most cases by changes in design, such as bushings, windings, terminal blocks, etc., each type of trouble being somewhat peculiar to some location or climate. These troubles are being cared for on present installations by the operating companies and the new products are being put out by the manufacturers according to specifications for the companies operating in the different localities.

4. *Fuses.* Metal parts on fuses for this class of lines should be so placed that there will be no discharge from the metal to the porcelain, or between the different metallic parts. The fuse wire in this class of fuses is subject to what is sometimes called corrosion and when this takes place, discharge to the side of the fuse tube usually occurs. The only remedy for this trouble is to replace the fuse wire. This trouble does not seem to occur where the tube is filled with a nonconducting dust.

Lines Under 5,000 Volts.

1. Interference from this source is comparatively slight and not as important as that from the higher

voltage lines. Poor connections are responsible for many of these cases, and loose fuses account for many complaints. Old type demand meters cause considerable trouble but there are comparatively few of them, they are easy to locate, and are being replaced very rapidly.

General. As an aid to utilities and more especially to electric companies in the elimination of interference the following from an operating company may be a helpful suggestion.

Early investigations brought to light the many points at which radio interference originates on pole line structures. In some cases the remedy was a change in standards to provide more clearance between the metal parts, and in other cases it was necessary to provide for proper bonding. In both instances it was found most advantageous to instruct the field forces not only by letter but by demonstrations and photographs. It is

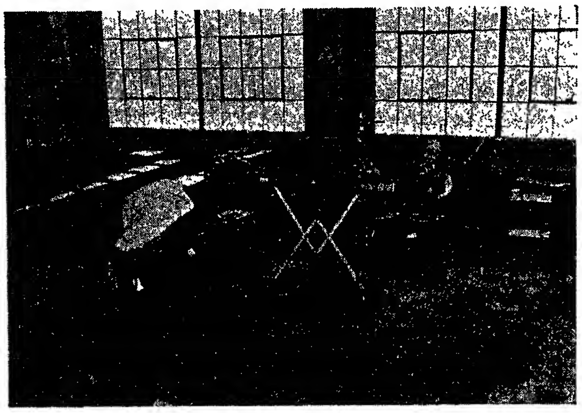


FIG. 4—POLE LINE RADIO INTERFERENCE DEMONSTRATION

somewhat difficult for the average man to believe that the noise which obliterates "Amos and Andy" comes from a spark smaller than a pinhead, and located between the ends of two crossarm braces. Accordingly a pole top was equipped with dead-end construction, a set of inverted braces, high-voltage sign, space bolts, etc., arranged to cause radio noise. (Fig. 4.) This structure was placed in the transformer warehouse and energized from the high-voltage side of a bank of 5-kw. 11-kv. transformers. This was done at night, in the dark, in order that each man could walk by, see the spark, and hear the noise in a radio set located nearby. This demonstration accompanied with explanations was given before all district foremen, and also before the workmen in many of the district headquarters with excellent results. Along with this demonstration, instructions were given on the proper bonding of 11-kv. air switches. Sample jobs of bonding were placed on the floor, and near the ground on poles just outside of the warehouse. Photographs (Figs. 5A and 5B) of these bonding jobs, together with instructions, were distributed and each district foreman posted these photographs and instructions on the bulletin board for the workmen.

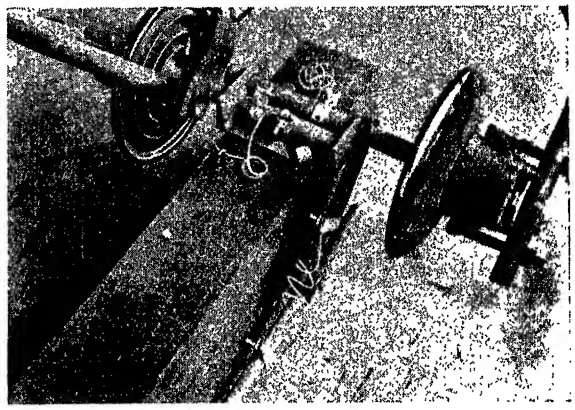
Electric Railways

Many power companies either own or are vitally interested in street railways. Their sources of interference are not numerous but very baffling.

1. Commutator sparking on the truck motors can be reduced by increased maintenance.

2. Compressor motor noise can be greatly reduced by making the connections so that the field goes to the trolley and the brushes to the track.

3. Trolley contact. There is not much to be done



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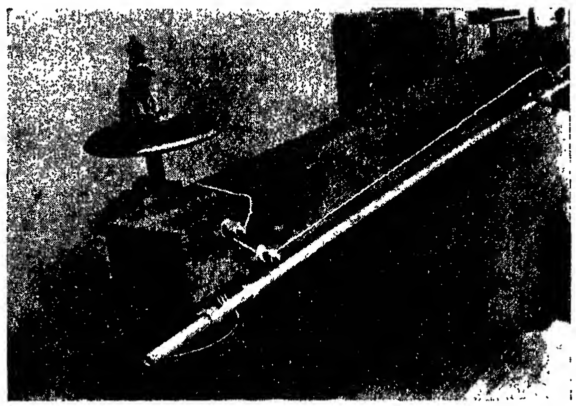

B

FIG. 5—BONDING DETAILS FOR AN 11-KV. AIR SWITCH

for this except a more frequent turning down of the trolley wheels and greater maintenance. In some cases, a shoe has been substituted for the wheel and lubrication of the trolley at the same time gives added relief from interference and longer life. This is only in the experimental stage at present. It would seem that the addition of grease would provide a means of partially smothering the small arcs, as the grease is melted, and some further study along this line may prove productive of good results.

4. Rail contacts. The only means of reducing rail contact arcing is to keep the rails and truck wheels clean. This is simply additional maintenance.

Communication Companies

Various units of apparatus associated with communication circuits for giving telephone and telegraph service may be sources of radio interference, among which are ringing machines, pole changers, telephone typewriters and dial telephones. These possible sources of interference are being given considerable attention by the telephone companies and those which would be expected to cause interference are usually treated at the time of installation. Other cases are cared for when and if interference is experienced. The suppression equipment generally used consists of retardation coils and by-pass condensers, sometimes used with resistors, applied singly or in combinations according to the needs of the case.

Industrial and Domestic Apparatus

Radio interference from this class of apparatus may be divided into three types: First, that coming from commutating apparatus,

Second, that coming from make and break contacts, and

Third, that coming from high-frequency apparatus such as violet-ray sets, diathermics and X-rays.

1. Commutating apparatus can be corrected by the use of two series condensers across the brushes, with the center point grounded to the frame of the motor. In larger installations it may be necessary to install air core chokes in the leads.

2. The make and break interference may be corrected by shunting across the contacts a resistor and condenser in series and in severe cases by the use of air core chokes in the leads.

3. To suppress the interference from high-frequency apparatus of this type it is usually necessary to have the room in which it is used thoroughly shielded and a suitable filter inserted in the supply leads.

4. General. It is possible to purchase filters to correct practically all the troubles under this heading. The proper selection may be obtained by either consulting a reputable dealer or writing direct to the manufacturer of these filters.

Paths of Radio Interference

In most cases radio interference is conducted and radiated by the power supply system. The distance conducted and radiated depends upon the power generating the spark, the width and resistance of the spark-gap, and the natural periods of oscillation of the power supply system and connected apparatus. The distance also depends upon the high-frequency impedance from line to ground. Transformers furnish a comparatively low impedance path to ground and a line with few transformers will carry radio interference a greater distance.

The interference reaches the receiving set by direct conductive coupling through the power supply wires or by inductive coupling between the power supply wires and the radio antenna-ground system, or by both paths. Some receivers pick up interference by the induction of interfering currents in the chassis of the receiver itself. The sensitivity of the modern radio receiver makes it possible to operate on an inside antenna or on a low short outside antenna. An inside antenna increases the coupling to the power supply wires and in many cases the power supply wires bring in most of the broadcast signal. This close coupling also makes the set more susceptible to interference feeding over the service lines. There may be fading when other loads are switched off and on if the service lines are functioning as an antenna. The fading can often be overcome by putting up a high outside antenna, grounding the power supply neutral wire at the entrance switch and in some cases tuning the house wiring with proper condensers.

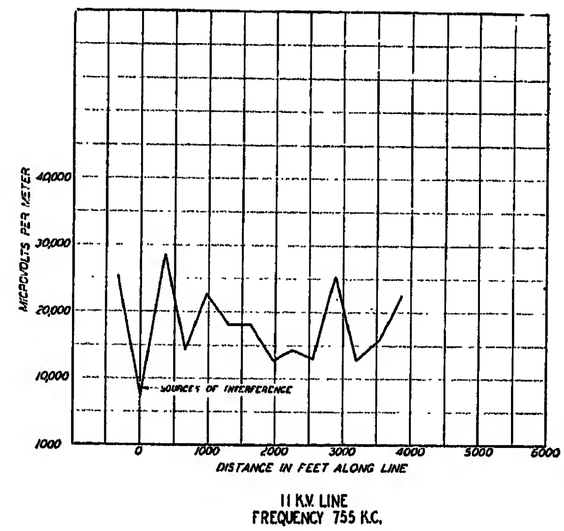

Fig. 6—Variation of Field Strength of Interference Along an 11-Kv. Line

Tracing Interference

A radio interference test set is operated necessarily from a battery source. It cannot conveniently be connected conductively to the power supply system. This makes a highly sensitive test set necessary in order to pick up the weaker interferences. Some of the cases of interference with an a-c. receiving set cannot be picked up by a battery test set unless very closely coupled to the lines. Contrary to earlier beliefs, sources of interference cannot be located by means of triangulation. The directional property of a loop antenna can be made use of at points of line intersections or at taps. This sometimes enables the operator to determine the circuit causing the interference.

The attenuation of high-frequency currents along wires does not follow the law of radiated electromagnetic field at right angles to the wires. Due to discontinuities of line constants, and reflection of

waves, there is a development of unequally spaced nodes and antinodes of intensity. The intensity is sometimes greater a mile from the source of trouble than near its immediate source. Changes in intensity of interference are caused by resonant points, variation of distance from wires, presence of metal structures near lines, reflection phenomena, ground wires, tap lines, right angle corners, changes in line configuration, etc. Due to changing weather conditions and to the changing characteristics of the spark, there is also a daily variation of the intensity of interference. Fig. 6 shows the effect of some of these conditions. The intensity at the source is less than at other points where measurements were taken. There is a rapid increase in intensity in each direction along the line up to 350 ft. from the source. At 3,800 ft. there is a tap line. The intensity increases rapidly at this point.

Fig. 7 shows the characteristic curve taken on a line

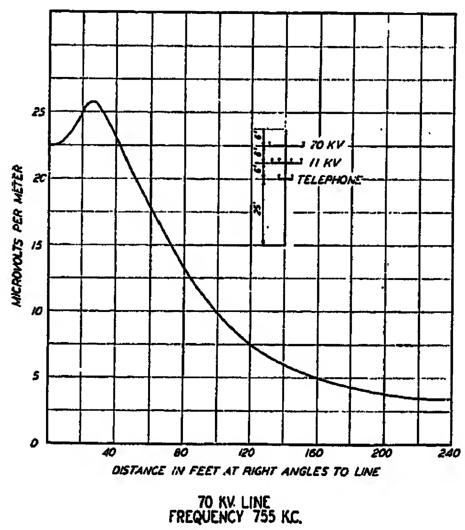

FIG. 7—VARIATION OF FIELD STRENGTH OF INTERFERENCE AT RIGHT ANGLES TO A 70-KV. LINE

insulated with pin-type insulators. It is interesting to note the peak, occurring at 25 ft. This is found on all such curves but the reasons are not definitely known.

In locating interference the usual procedure is to use an intensity method. The effect of noise upon the human ear is not a straight line function and the ear cannot be depended upon accurately. A close inspection of equipment and the use of low-frequency exploring apparatus at suspected points usually shows the source of trouble. An investigator learns to keep on the right track by noting changes taking place at various locations as he drives along the line.

Experience is an important advantage in favor of the interference investigator. He must have a maximum of patience and persistence in actually tracing sources of interference. He should also be a man capable of meeting and intelligently talking to the public.

Elimination of Interference

In general, the most satisfactory method of overcoming interference is stopping it at its source. From the power company standpoint, good radio construction and maintenance of power lines are important in order to avoid creating new sources of interference, thus forestalling future complaints. If the source of interference cannot be corrected, filtering at the source or isolating sections of lines by low-pass filters may be the best possible solution. Preventing the spread of interference by filtering transmission and distribution lines may not be practical from an economical or operating standpoint. Further study of the application and design of filtering devices is needed as each individual case may require special consideration.

The elimination of radio interference from industrial and household electrical devices can best be done at the factory by the manufacturers of such devices. Some manufacturers are and have been for some time aware of the radio interference problem and have taken steps to overcome it.

A method sometimes successfully used to overcome interference from all electrical sources, when the maximum noise pickup is from the service lines, is the use of a filter in the power supply lines at the receiver. In such cases a high outside antenna with a shielded lead-in and shielded ground connection must be installed in addition to the filter. This method of eliminating interference will not be satisfactory when the greatest part of the noise is picked up on the flat top part of the antenna. When no shielded lead-in is used it is very important to keep the lead-in and ground wire as far away from the interior house wiring as possible. Radio ground connections to steam pipes should be avoided and in no case should gas pipes be used. Where possible to install, a good independent ground rod is recommended.

Conclusions

From the foregoing it is easily understood that there is no simple solution for the interference problem, but it must be dealt with in a spirit of cooperation by the utilities, electric manufacturers, and the public. The interference from electric power supply systems is well in hand except for the troubles originating on high-voltage lines. Although filters on power lines have been suggested their use is yet very questionable. Manufacturers have a great opportunity in the sale of radio noise-proof appliances and apparatus. The public can aid by insisting upon such appliances.

In congested areas, radio trade interference associations have proved valuable to all concerned, while in the less thickly populated areas clearing interference is still left principally to the utilities. Increased broadcast coverage is very desirable to offset the natural noise level in many of the large areas now having low-field strengths as new and additional noises will always be

experienced. Continued cooperative effort on the part of all concerned is undoubtedly the best solution to this problem which has come to be paramount to millions of people depending more and more on the radio for entertainment and education. The expression that the United States is becoming "noise conscious" may very appropriately be applied to the radio listening public.

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Discussion

J. J. Smith: The large increase in complaints recorded in Fig. 2 of Messrs. Campbell and Kalb's paper is, I think, typical of the experience of many power companies and shows that the solution of the problem of radio coördination is still in the future. The authors have given a list of sources of interference which is very similar to lists given elsewhere. It is to be regretted that they were not able to amplify their observations on these sources by the addition of field strength data of the type given in Figs. 3, 6 and 7, measured in cases where trouble was experienced and also after remedial measures had been applied.

Our experience to date would seem to show that in one case a complaint may involve a disturbance with a field strength of the order of 10 microvolts per meter, in another 100 microvolts per meter, and in another 1,000 microvolts per meter. Which of these complaints is a legitimate one? This is a question which many are asking and at least one public utility has already taken the position that it will not accept responsibility for complaints unless the broadcast signal strength at the point of reception is of a reasonable level. The criterion used at the present time is that the disturbance must be of sufficient intensity to interfere with the reception of the nearby stations.

About five years ago changes were made in a piece of apparatus so that when it was tested in close proximity to the radio sets being manufactured at that time no noise was heard in the set. In general, such changes cost money and make the apparatus more expensive. With the introduction of more sensitive sets in the last few years complaints have been received that disturbance to radio reception has been caused by some installations of this apparatus. Should it be changed again to conform to present conditions with every likelihood that something further will have to be done in another few years?

These points are mentioned to show that the question of responsibility is more involved than would be assumed from the three last paragraphs in the section entitled "Responsibility" in the paper.

It has been apparent for a considerable time that the problem cannot be solved by the power companies nor the manufacturers of power apparatus nor the manufacturers of radio apparatus acting alone. Cooperation among these interests and with others will be necessary. To further such cooperation a Joint Committee on Coordination of Radio Reception of the N.E.L.A., N.E.M.A. and R.M.A. has recently been organized with a view to studying the problem as a whole so that the public may have the use of power and radio facilities in the most economical manner. Similar joint work on coordination of power and telephone systems which was described in a series of papers at the A.I.E.E. Winter Convention, 1931, has given very gratifying results and it is to be hoped that the work on radio reception will be equally successful.

The work being done by the authors can be of considerable value to this Committee if carried out in a quantitative manner so that the measurements in one locality can be compared with those in another. From such measurements and similar ones made by other investigators reasonable practises to be followed by power companies, manufacturers of power and radio apparatus, etc., will gradually be evolved.

Leonard F. Fuller: Table I of this paper shows a marked increase in the percentage of radio interference cases due to the power company within the last few years, whereas the percentage due to other causes has remained substantially constant, and that of cases clearing themselves has decreased to approximately one-half of the 1924 figure.

I ask the authors for an explanation. Offhand one would expect the percentage due to the power company to decrease with accumulated experience. The reduction in the percentage of cases clearing themselves seems entirely logical.

Referring to the ratio of field strengths of K.P.O. and K.F.R.C., it should be noted that field strength varies as the square root of the *radiated* power, and not in direct proportion to the *rated* power. In the case of these stations, one would expect a $\sqrt{5}$ to 1 ratio between their field strengths provided the powers radiated from their respective antennas have the same ratio as the station kilowatt rating, namely, 5 to 1. This would be the case if their antenna effective heights and resistances were equal. Unexpected reduction in field strength ratio with distance as observed by the authors is probably explained by the many factors affecting attenuation with distance.

One of the authors informs me that a 5 to 1 field strength was mentioned merely because many engineers erroneously believe field strengths are directly proportional to station power rating.

J. O'R. Coleman: There are a few conclusions drawn in this paper relating to the subject of radio interference and revenue with which I do not entirely agree.

On page 82 the authors estimate that the revenue to the central station industry from 15,000,000 radio receivers amounts to about $100,000,000. The total revenue of all light and power companies of the United States, from domestic consumers for the year 1930, amounted to $668,500,000. According to estimates of the National Electric Light Association, based on information collected from a few representative power companies, the revenue to power companies for the whole of the United States, to be credited to radio receiving sets, is now between $30,000,000 and $35,000,000 per annum. The electric refrigerator, electric range and the electric flat iron are appliances which account for much larger annual revenue than the radio receiver. The radio receiver, of course, gives a very substantial and desirable revenue but it cannot be considered as outweighing all other uses of electricity, either in importance from the central station standpoint, or in importance to the ultimate consumer who uses the electricity for the above appliances as well as vacuum cleaners, washing machines, toasters, fans, percolators, etc.

Then there is the question of definition of interference as applied to radio. Apparently the authors of this paper consider that interference is any electrical disturbance which will prevent satisfactory radio reception more or less regardless of any of the many other factors that enter the problem. Consideration of interference is as old as civilization itself. We all recognize that we have to restrain some of our liberties in order that we can live with other human beings. There were questions of interference between railway bridges and steamships in the early days of transportation. Practically all electrical engineers are more or less familiar with the many problems relating to interference which have confronted the power and telephone industries since their very beginning. These problems have not all been solved to this day, but both industries, by recognizing duties as well as rights, have been able to develop their extensive and now indispensable systems without any undue burden placed on either by the requirements of the other system. The telephone com-

pany would not even try to render its service in the city of San Francisco with the ground return circuits which at one time were considered not only the last word in communication systems, but practically the only way that a commercial telephone system could be operated. In the study of the coördination of power and telephone systems we have found that the problem naturally divides itself into a study of influence of the power system, a study of the coupling between the two systems, and a study of the susceptiveness of the telephone system. In the principles and practises between the National Electric Light Association and the Bell Telephone System, it is recognized that each industry will limit these factors so far as necessary and practical. It appears to me that the same treatment could be applied in the handline of radio coordination. Of course, there must be a limitation of disturbing fields, but there must also be some limitation of the susceptiveness of the radio receiver and of the coupling between the radio receiver and other electrical systems.

Electrical disturbances which in no way affected the radio sets of five or six years ago, today are frequently complained of as serious sources of interference. Technically, it is possible to increase amplification of signal strength very much further than is practised today. The present limitations on increase in amplification, are the noises produced by the agitation of the molecules of the conducting material. If this is to be the limit of the radio receiver for which other uses of electricity are to be held responsible, we will certainly place a serious burden on power, light, communication and transportation.

The authors state that it is the responsibility of the appliance manufacturers to see that all appliances are completely free of radio interference. The same individuals pay for appliances that pay for radio sets, for communication service, and for power service. The authors have pointed out the particular problem which exists in the San Joaquin Valley, due to low field strengths. However, they advocate that the increased cost of appliances be forced upon all consumers in order that this problem, which is confined to limited localities, may be eliminated. Suppose that the filtering devices which are advocated for vacuum cleaners should add only one or two dollars to the cost of vacuum cleaners. This would add a serious increased total cost of appliances to the public. It is a question as to whether such a cost is justified.

Recognizing that this problem was not to be solved by placing an undue and unnecessary burden upon any one class, the Radio Manufacturers Association approached the National Electric Light Association and the National Electrical Manufacturers Association, to enter with them in a joint study to determine the best overall solution of the difficulty. This joint committee, with seven representatives from each of the three industries concerned, has had several meetings and is now working on this problem. This committee does not hope to find a solution for the problem today or tomorrow, but it hopes to find a solution which will be fair to all parties concerned, and give the best overall economy to the public which we are all striving to serve.

Broadcast Coverage

F. B. Doolittle: The need for better broadcast coverage in California as pointed out by Messrs. Campbell and Kalb, is made more apparent by inspection of a map of the state in which the areas enjoying reasonably good reception are designated and may be compared with the total area of the state. This map (Fig. 1) was prepared by the Railroad Commission of the State of California, which, after an extensive investigation, over a year's time, submitted it as a part of its report to the Governor on "Interference with Radio Broadcast Reception in the State of California," under date of December 1, 1930.

There is little doubt that California has a sufficient allotment of broadcast power and frequencies to serve the area adequately, but the geographical distribution is such that reliable service is not available to large areas and actual inconvenience is worked upon other places by an excessive number of stations in thickly populated centers. There are eighteen broadcast stations in the metropolitan area of Los Angeles, all of them trying to serve the same group of people. One of these stations broadcasts "Amos and Andy," yet many listeners in this area must receive this popular program from a station one hundred thirty miles away because of inability to separate this program from that of other local stations. Would it not be a blessing to all concerned if some of these eighteen stations could be relocated to render service where service is needed?

Elimination of Interference from Industrial and Domestic Apparatus

To cope successfully with the problem of elimination of interference from industrial and domestic apparatus, a definition of radio interference is required. Such a definition is difficult to formulate because, for example, a series motor-driven household appliance may interfere with radio reception in a whole neighborhood in a region of low broadcast signal strength and yet its operation at a location close to broadcast stations may cause no complaint. It is agreed that corrective measures are required on such apparatus in some locations, but is it economically sound to add to the cost of all appliances for the benefit of radio reception in certain areas where they might be used? The ideal answer to this would be to develop non-radio interfering apparatus at no additional cost. If this is not possible, a definite limit of the permissible amount of interference might be established by means of sufficient economic research.

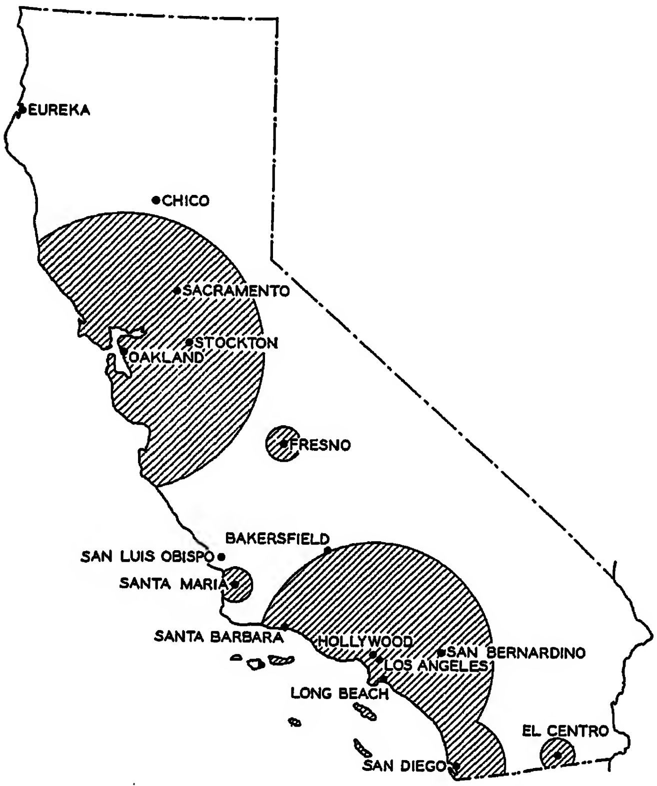

Fig. 1—Map of California Showing Area within Satisfactory Reception Range of Broadcast Stations

Assumed range of 5,000 watt station,—100 miles. Assumed that distance varies as square root of transmitting power. KNX limited power license for 50,000 watts not considered

The use of filters with appliances where necessary is an obvious solution of this problem which possesses the advantage of being applicable to appliances now in service as well as to new ones. However, tests made with simple filters or rather radio frequency shunts consisting of two one-tenth microfarad condensers in

series across the motor brushes with the common point connected to the motor frame proved them to be only partially effective. The average reduction in radio frequency voltage generated by five different appliances with this method was 81 per cent at 1,200 kilocycles and only 67 per cent at 600 kilocycles. A more elaborate filter consisting of series inductances and shunt capacities reduced the radio frequency voltage an average of 98.6 per cent but the retail cost of this filter was 60 per cent of the average price of the appliances and more than three times the price of one of them.

From the foregoing it will be appreciated that this problem of radio interference from industrial apparatus and household appliances is not one which can be simply dismissed by putting it up to the manufacturers to provide such equipment with condensers, but is rather a problem involving many technical and economic aspects which can only be solved satisfactorily by cooperative research involving the public, the electrical manufacturers, the radio industry, and the central stations.

Responsibility

The authors have pointed out the increase in interference complaints brought about by the increased sensitivity and susceptiveness of modern radio receivers. Since this is true, a partial solution would consist of limiting those properties of receivers to a certain degree. The susceptiveness of receivers due to conductive coupling to the power supply circuits can be largely eliminated by proper shielding and filtering by the manufacturers of the receivers. As proof of this statement it is only necessary to refer to several popular receivers which are so constructed that without an antenna no interference or broadcast can be tuned in. Limiting the sensitivity to a reasonable degree would compel the installation of an adequate antenna which when well located would react favorably on the signal to noise ratio. Since many of the sources of interference have existed for years and would require very large expenditures to correct, it would seem only reasonable that the radio industry, the new-comer in the field, should shoulder its portion of the burden by cooperating to the extent of seeing that sets are designed and installed with antenna and ground systems of minimum susceptiveness. This calls for education of retail dealers and their installation men.

The authors have truly sounded the keynote in the situation when they call for "close cooperation between parties responsible for radio interference in order that the best possible public service may be given in the most economical manner."

F. E. Terman: The difficulties that are encountered in tracing down and eliminating sources of radio interference produced by high-voltage lines make it of interest to know exactly what this interference consists of. Mr. Overacker who is registered in our Electrical Engineering Department has done considerable work during the past year on interference problems in cooperation with Mr. Kalb. He finds that in the immediate vicinity of the trouble which generates the radio interference the disturbances received by the radio receiver may be caused either by radiation, or by induction through inductive or capacitive coupling between the radio antenna and the transmission line, but that at some distance down the transmission line from the source of the noise the interference is received only by direct coupling with the transmission line. A consideration of the factors involved indicates that this is a highly reasonable result, as the radiated field is inversely proportional to the distance from the radiator and so dies out relatively rapidly with distance, as is indicated by Fig. 7 of the paper, whereas the high frequency currents propagated along the line by ordinary transmission line action for great distances before being appreciably attenuated, but do not produce radiation and so cause interference only by direct coupling.

R. N. Stoddard: In order to coordinate radio interference satisfactorily, it is essential that a method of measurement and a unit of measurement be standardized. This work is now in progress through the Joint Coordination Committee on Radio Reception of N.E.L.A., N.E.M.A., and R.M.A.

It is recognized that the degree of interference may be expressed by the ratio of the useful energy to that which is disturbing or interfering, and that the degree of interference may be modified by a change in this ratio. Interference may be minimized by either an increase in the useful energy or by a decrease in the disturbing energy. Considerable studies have been made of field strength associated with individual broadcasting stations. Some studies of interfering levels have been made by various central stations and utilities. All available data are being collected and coordinated by the Committee and it is hoped a base unit of reference can be arrived at which will be satisfactory to all. This figure will determine the permissible degree of interference based upon a certain minimum serviceable field strength from a broadcasting station.

The authors point out that in general the most satisfactory method is to overcome the interference at the source. It is felt, however, that this should not be taken too literally as prevention of interference at its source may not only be more expensive than other methods, but might be impossible at the present state of the art.

The authors' conclusions state that the use of filters on power lines is yet very questionable. This is in sharp contrast to the sentiment and practises of several utilities in the east. It is felt that the application and use of filters on power circuits have been eminently successful in preventing interference in telephone circuits, carrier current channels, and radio broadcast receivers.

Filters have been applied to the neutrals of generators directly feeding transmission lines to prevent the harmonic frequencies disturbing telephone communication circuits. They have also been quite generally applied to mercury arc rectifiers for the same purpose. High-voltage transmission lines have been filtered to prevent interference between power line carrier communication channels on the same or adjacent interconnected systems. Filters have also been used to simplify high frequency characteristics of complicated transmission line networks.

Remarkable success has been achieved in filtering radio frequency interference from transmission lines particularly where some individual line is coupling the interferences to the secondary or distribution circuits. While it is realized that filters are not the general solution to all interference problems, they have formed a successful and economical solution in many cases of transmission line troubles. It is therefore felt that the application of filters to transmission lines should not be considered as questionable.

C. C. Campbell and H. N. Kalb: Dr. Fuller points out the rapid increase in the percentage of radio interference complaints due to the power company within the past few years, as shown by Table I. This increase was caused by the omission from the table of complaints investigated by Radio Trade Associations in metropolitan areas since 1928. In metropolitan areas the percentage of complaints due to the power company is considerably smaller than in other areas.

Mr. Coleman advises that the estimated annual revenue from radio sets was $35,000,000 instead of $100,000,000, as estimated in the paper. This estimate was made with reports of Pacific Coast Companies as a basis, and may not apply to other parts of the country.

Backfires in Mercury Arc Rectifiers

BY J. SLEPIAN* and L. R. LUDWIG*
Fellow, A. I. E. E. Associate, A. I. E. E.

Synopsis.—Mercury arc rectifier design of today was arrived at in an endeavor to reduce the frequency of backfire. Efficiency and cost are sacrificed to obtain sufficient backfire immunity.

Study of backfires in actual rectifiers and laboratory tubes indicates that this occurrence is a random one. Backfires differ in kind from other breakdown phenomena because they do not occur with certainty after some definite limitation has been reached, and in fact no limit can be chosen above which or below which backfires will or will not take place.

The state of a rectifier in relation to backfiring must be described in terms of a backfire probability, or average rate of backfire. There are no commercial tank rectifiers for which the mean frequency of backfire is absolutely zero, but some probably reach the low value of one per several years.

The significance of the random nature of backfire on the rating and testing of rectifiers is discussed, and suggestions are made as to means for testing which lead to the determination of the true quality of a rectifier.

Data are given showing the variation of the backfire rate with current and voltage. The application of these ideas to research and development is illustrated by several examples.

The theory of the formation of a backfire is described, and backfires are attributed to "causes" which lead to the formation of a cathode spot on an anode, but which do not correspond to any fundamental limitation of the rectifying process. Several suggestions are made as to the exact nature of these causes.

The time duration of these causes has been found with the cathode-ray oscillograph to be very short, of the order of a few microseconds.

The authors dispute the theory that there is a continuous transition from a discharge of the glow form to that of the arc, at least in the case of the backfiring of mercury arc rectifiers.

* * * * *

Section I

INTRODUCTION

IN a normally operating mercury arc rectifier, each anode carries a large current when it is at a positive potential with respect to the cathode and only a small current of the order of a few milliamperes when it is at a considerable negative potential with respect to the cathode. It was found early, however, that with the simplest and most obvious constructions this normal operation was not reliable, and moreover acted in an erratic way. An anode would function properly cycle after cycle over a greater or lesser period of time, and then suddenly fail to hold voltage when negative in some particular half cycle. Such failures of anodes to bear negative voltage and thus cause short circuits are called arc-backs or backfires.

The causes of these backfires are not at all well understood even today, but it was found early that certain constructions greatly reduced the likelihood of their occurrence. Thus it was found that provision of adequate means for cooling the rectifier, moving the anode away from above the cathode, the use of shields around the anodes and grids interposed in the arc path to the anode, and the exercise of extreme care with respect to cleanliness in assembling the rectifier and the removal of all foreign gas to the highest possible degree, all reduced the backfire probability. Thus practically the whole design of present-day rectifiers is based on the endeavor to reduce the frequency of occurrence of backfires and this has caused many of the advantages to be sacrificed which might be expected from the application of the normal characteristics of the mercury arc to the rectifier problem. It seems clear that research for the purpose of advancing the application of mercury arc rectifiers must be largely directed to a study of the nature of backfires so that means may be devised for reducing the frequency of their occurrence without losing the attractive features of mercury arc conversion.

Section II

BACKFIRE—A RANDOM PHENOMENON

The erratic manner of occurrence of backfires thrusts itself upon the attention of all who have to do with rectifiers; not only upon erudite research men in the laboratory, but also upon operators in the field. Yet the great significance of this erratic behavior is not realized; and its implications as to the operation which properly may be expected, as to the correct rating of rectifiers, as to the testing of rectifiers, and as to the appropriate methods for research and development do not seem to have been generally grasped.

It must be recognized that except for backfires due to certain grosser causes, some of which will be mentioned later, backfires are inherently random phenomena.* They differ in kind from other breakdown phenomena, or at least they differ so greatly in degree as to be practically different in kind. Let us compare, for example, the backfiring of a rectifier with the breakdown of a spark gap in air at ordinary pressures. As the voltage on a spark gap is gradually raised a point is reached where the spark gap breaks down. If voltage is again applied to the spark gap and is raised up to a point just short of the voltage at which the previous break-

*Research Laboratories, Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

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*Since this paper has been written, a paper has been published in the *Revue Generale de L'Electricite* of June 6, 1931 and of June 13, 1931 by M. Leblanc and Demontvignier, which also cites the random nature of rectifier backfire. Furthermore a recent review of patent literature by the authors disclosed a patent of Chas. A. Kraus (U. S. No. 1,086,300) which refers to the random nature of backfire.

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down occurred, then the spark gap will not break down. The spark gap will bear this lower voltage indefinitely without breaking down. If, however, the voltage is raised slightly above that at which breakdown occurred in the first test, the spark gap will at once break down. No matter how often this test is repeated the spark gap will be found unable to support the higher voltage for any appreciable length of time.

Now consider the backfire in a rectifier. As the load upon it is increased there will be a point where a backfire occurs. If now the load is reduced below this value, will the rectifier function indefinitely without backfire? Not at all. Backfires also occur at the lower load at random moments. If the load is lowered still further, backfires still occur at random; much less frequently it is true, but they still occur. Conversely if the load is increased above the critical value found in the first test, will backfire occur at once? Not at all. The rate of backfire occurrence is increased, but the rectifier may carry the higher load for one minute or for ten minutes, or maybe only for one second, depending seemingly on chance as to how long the run can be without backfire.

Thus backfires in a mercury arc rectifier seem to occur not under definitely limiting conditions, but under all conditions in their random manner, with an average frequency which depends upon the conditions of operation, and the construction.

Inherently and fundamentally random or erratic phenomena are well known in physics. They usually involve aggregates of a small number of molecules making up small particles of matter. An early example of such phenomenon is the Brownian movement. Brown, an English naturalist, discovered with his microscope that very fine particles of matter suspended in a liquid were in a state of continual motion moving about in a random helter-skelter manner. Such motions are also observed on smoke particles in the air. The explanation of these motions is that the number of molecules of the surrounding liquid or gas which collide with the one side of the particle may not, at a particular moment, agree with the number of molecules which collide with the other side of the particle. Thus there are continual unbalanced forces upon the particle arising from these collisions of the molecules of the medium and because of the smallness of the mass of these particles under these forces, the particle is given a random motion. In the motion of the particle under the Brownian movement, displacements of the particle in various directions are continually taking place. Moderate displacements happen frequently, large displacements less frequently, and very large displacements only very rarely. However, there is no sharp limit as to what displacement may occur. It is merely that the probability of occurrence of a displacement becomes small when the displacement becomes large. If the size of the particles is increased, the magnitude of the displacements occurring as a result of the Brownian movement becomes less. However, large displacements continue to occur, but less frequently than with the small particles. When the particle becomes of ordinary size, say like a billiard ball, then the Brownian movement becomes exceedingly minute, and deviations from the normal motion of the ball under the gravitational field predicted by every day mechanics, become generally indistinguishable. However, a considerable deviation from the regular motion should continue to be expected, but with the frequency of occurrence so low that it should be expected to occur only at a rate of once in tremendous eras of time.

Another more modern example of an inherently random phenomenon is the disintegration of radium. The atoms of radium explode, but apparently in an entirely random way so that in one short interval of time a large number of molecules may explode and in another short time interval only a small number of molecules may explode. The scintillations which are observed on suitable screens in experiments with radium are visible evidence of the random character of the radioactive decomposition.

The backfires are also inherently random occurring phenomena and probably likewise depend for their occurrence upon aggregates involving relatively small numbers of atoms, molecules, ions, or electrons.

Section III

Distribution of Backfires in Time. Mean Frequency of Backfire

The entirely random occurrence of backfires in time may be illustrated by the curve, Fig. 1, which was obtained with a small metal tank rectifier in the

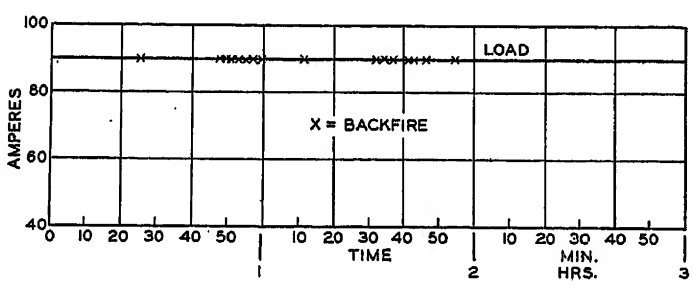


Fig. 1—Random Occurrence of Backfire on a Small Metal Tank Rectifier

laboratory with all controlling conditions maintained as nearly constant as possible and with a constant direct current to one anode and a constant test voltage on the other. This curve cries out that the occurrence of backfire is a matter of probability.

In concept at least we may define the probability of backfire of a rectifier in a particular condition, and during a short time interval Δt in this way. Imagine a large number N of tests made with a rectifier under identical conditions, the duration of each test being the short time interval Δt. Suppose that in a certain number of these tests n, backfires occur, but not in the

others. Then $\frac{n}{N}$ will be the probability of occurrence of a backfire in the time Δt, and if we write

$$\frac{n}{N} = p \, \Delta t$$

then p is the probability of backfire per unit time for the rectifier in the particular condition.

It is shown in Appendix I that if the probability of

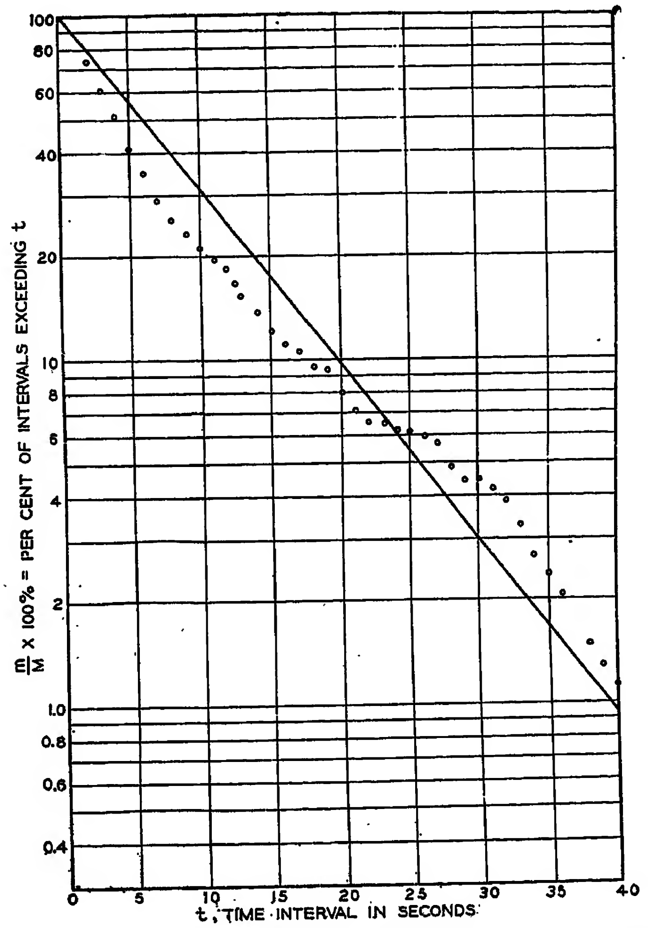


FIG. 2—LOG PLOT OF TIME t, AGAINST PER CENT OF BACKFIRE FREE INTERVALS EXCEEDING TIME LENGTH, t

backfire of a rectifier operating under constant conditions remains constant, and if the time intervals between successive backfires are observed, then the proportion of these time intervals which is greater than a time interval t will be given by e^{-pt}; that is,

$$\frac{m}{M} = e^{-pt}$$

or

$$\log \frac{m}{M} = -p\,t$$

where M is the total large number of intervals between successive backfires observed and m is the number of these intervals which are greater than t in length. This relation has been confirmed experimentally by D. E. Marshall using a glass tube with voltage higher than that necessary for maintaining a glow with results shown in Fig. 2, and by F. A. Maxfield for a metal tank rectifier with a constant current arc going to one anode and with test voltage on the other at a value insufficient to maintain a glow by itself, with results shown in Fig. 3.

From the equation above which gives the distribution of time intervals between successive backfires, we find that the average interval is $\frac{1}{p}$. This average interval is not the interval of most frequent occurrence. There is no tendency for backfires to occur at anything like regular intervals. As a matter of fact short

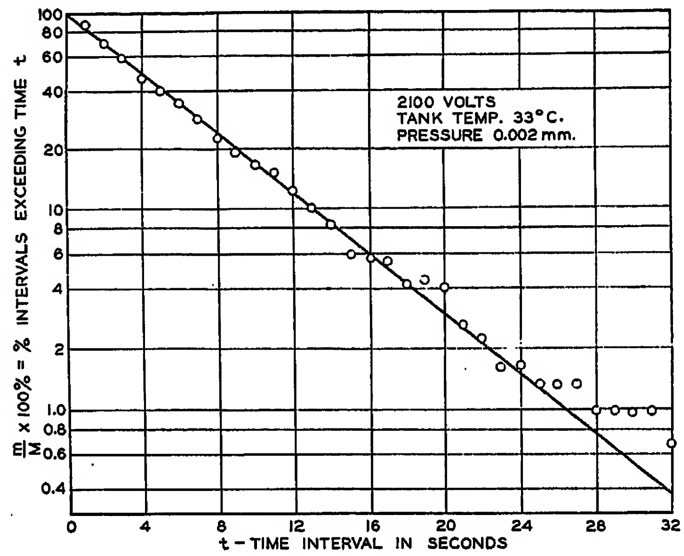


FIG. 3—LOG PLOT SIMILAR TO FIG. 3 EXCEPT THAT DATA WERE OBTAINED WITH A METAL TANK

intervals occur more frequently than the average, $\frac{1}{p}$. The average frequency of backfire per unit time is p, and $p\,T$ is the average number of backfires in the time T.

The state of a rectifier with respect to backfire is then properly described when a mean frequency of occurrence of backfire is given and it cannot be described by saying that the rectifier is operating below or above backfire limits, inasmuch as there are no definite backfire limits. The average frequency of backfire is a function of the construction of the rectifier and the conditions under which it is operating. Thus, under light load the probability of backfire or the mean frequency of backfire is small and under overload the mean frequency of backfire is large. But this does not mean that the rectifier will never backfire on light

load or is certain to backfire in a particular finite time interval on overload.

Of course for practical purposes a sufficiently small frequency of backfire is just as good as zero frequency of backfire; for example, a rectifier with mean frequency of backfire of one per ten years will be more reliable than the other electrical apparatus working with it and far more reliable than the human beings operating it. The backfire frequency of successful rectifiers in the field seems to be of the order of several per year.

Section IV

Testing of Rectifiers

The purpose of commercial tests on rectifiers is to determine their quality and to make sure that they come up to standard; but the quality with respect to backfire propensities must be determined in terms of an average backfire rate. Since the average backfire rate is very low for commercial rectifiers, the determination of this rate by the usual tests under normal conditions is practically impossible.

As an example, suppose that a considerable number of rectifiers were made with such uniformity that the average backfire rate for each rectifier was one per month on normal load; suppose that the manufacturer tested each rectifier on normal load for one month, which is an impractically long test. Then, as shown in Appendix II, 37 per cent of the rectifiers probably would not backfire during the test and 26 per cent would backfire twice or more often. Thus, although all of the rectifiers were of uniform quality and although the test was impractically long, 37 per cent would appear to be above the average quality and 26 per cent below. Testing under normal load for short time is only good for reliably weeding out rectifiers with exceptionally large backfire rate; and at the same time such tests will occasionally reject good rectifiers.

The way out of this dilemma seems to be to test the rectifiers not under normal conditions, but under such abnormal conditions as will make the backfire rate countable in a reasonable time and to have sufficiently well established data to permit extrapolation for determining the backfire rate under normal conditions. For example, if the dependence of backfire rate upon test voltage is well established for any particular type of rectifier, the tests on such a rectifier might be made at such overvoltage as will give a considerable number of backfires in one day. The extrapolation to normal voltage will give backfire rate to be expected under normal conditions.

Section V

Short Time Rating of Rectifiers

In many fields of application of rectifiers, as for example, electric railways, it is desirable that the rectifiers be capable of carrying overload for relatively short periods of time. Dynamo electric machines, transformers, etc., inherently have overload capacity because the limitation to their load carrying capacity is usually determined by the temperature of insulation and because it takes time for the various parts of the machine to acquire their final temperatures under overload.

But with the mercury arc rectifier it is different. It is true that the temperatures in a rectifier may change in time with overload so that the rectifier may get progressively worse from the standpoint of reliability. But apart from such progressive changes, before the temperature and vapor pressure have changed appreciably, the rectifier is immediately less reliable on being overloaded. This fact may not be recognized because of the shortness in time of the usual overload tests and because of false analogy with other types of electrical machines. As an example, increasing the load upon a rectifier to 150 per cent of normal might be expected to multiply the average backfire rate by perhaps ten. If we assume the rectifier is thus overloaded 10 per cent of the time, then if we take the multiplying figure of 10, this overload operation will double the number of backfires per year. If we should take a multiplying figure of 100, it will multiply the number of backfires per year by 11. This reduced reliability under overload will exist in spite of the fact that the rectifier successfully goes through the overload period day after day without any apparent distress.

Section VI

The Variation of Backfire Rate with Current and Voltage

The preceding discussion has brought out the great practical value of knowing how the average backfire rate may be expected to vary with such control factors as voltage and current. Regarding the dependence upon voltage, Fig. 4 shows the results obtained with a small metal tank, two-anode rectifier whose dimensions and circuit are illustrated in Fig. 5. Current was kept flowing to one anode and negative voltage was continuously applied to the other. Grid glow tube relays were used to record automatically the backfires upon a counter.*

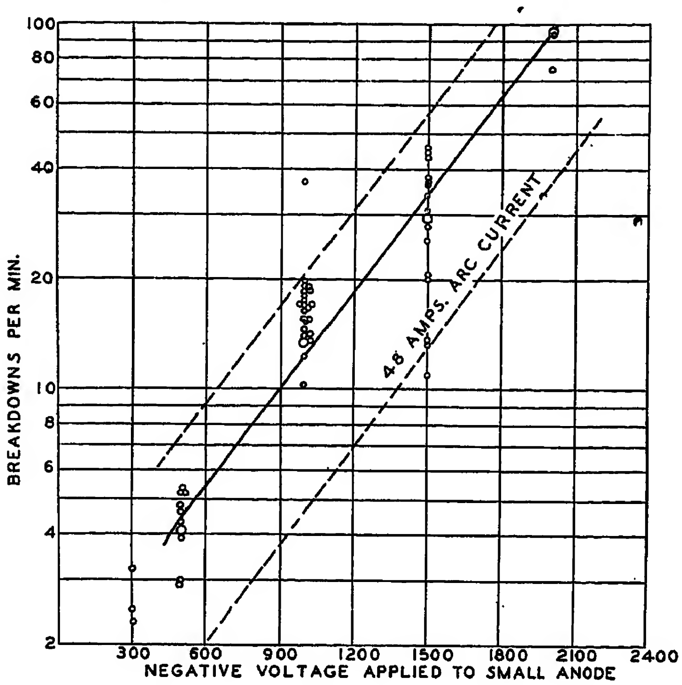
The average backfire rate seemed to vary exponentially with the voltage giving approximately a straight line on the logarithmic scale shown in Fig. 4. The tests were repeated at various times and different straight lines were obtained as the quality of the rectifier changed for unknown reasons. All the lines obtained lay between the dotted lines shown in Fig. 4.

Some data on the variation of backfire rate with current are given in Fig. 6. The two-anode metal tank

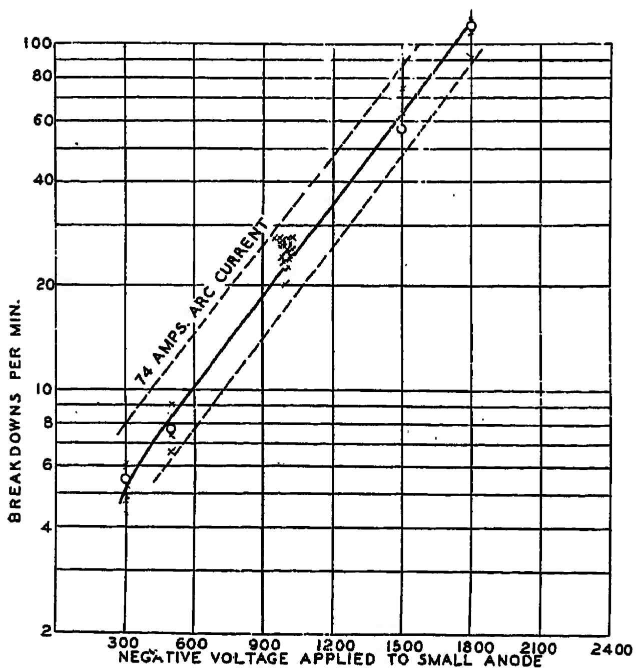
*When a backfire occurred, the charged condenser from which the negative voltage was obtained, discharged through the tank. This discharge current was limited by resistance to a value of a few amperes. After the backfire was completed, the condenser recharged so that negative voltage was then again applied to the anode. The data were obtained by counting the number of backfires in periods of 30 minutes duration. The tank temperature was held constant at 10 deg. cent. during the entire test.

rectifier illustrated in Fig. 5 was again used. Constant test voltage was applied to one anode and the current to the other anode was varied.

In applying the results of this experiment to rectifiers



A



B

FIG. 4—AVERAGE BREAKDOWN RATE AGAINST VOLTAGE FOR METAL TANK RECTIFIER

operating in a-c. circuits, it might seem that sufficient importance is not attached to the moment immediately following the change in direction of the voltage applied to an anode, as it may be thought that backfires occur most frequently then. However, experience shows that this is not the case, so that even if the probability of backfire is high at the moment of voltage reversal, the shortness of this moment more than makes up for the magnitude of the probability with the result that backfires appear to occur more often sometime later than the reversal rather than immediately after it.

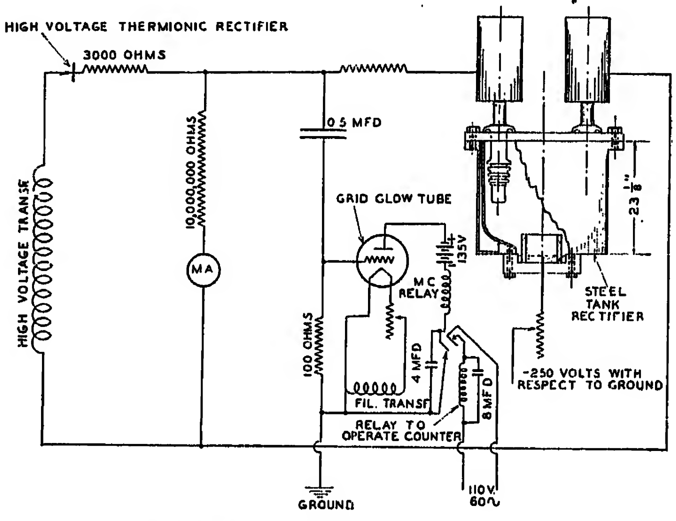


FIG. 5—METAL TANK RECTIFIER TEST CIRCUIT

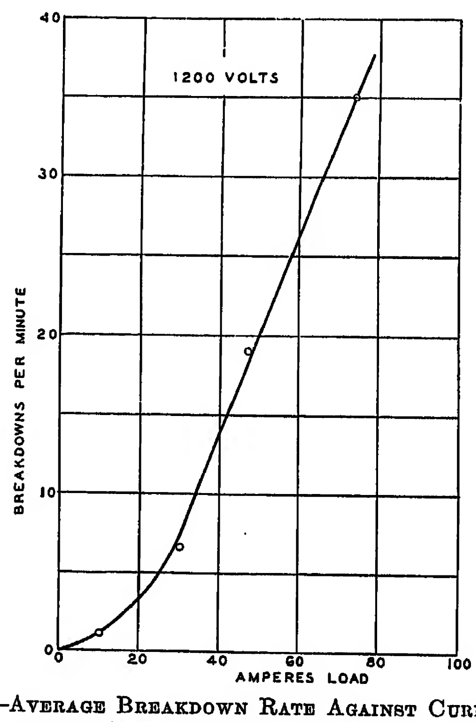


FIG. 6—AVERAGE BREAKDOWN RATE AGAINST CURRENT FOR METAL TANK RECTIFIER

Section VII

APPLICATION TO SOME RESEARCH PROBLEMS

The difficulty encountered in determining the proper rating of rectifiers by tests under normal conditions of reasonable duration is also met in researches whose purpose is to determine the relative merits of various constructions or materials entering into rectifiers. For

example, consider the question of material for anodes. Graphite anodes are now used by many manufacturers in metal tank rectifiers, but iron anodes are also used extensively. The practise does not seem to be uniform, and may be changed as a result of longer tests. The reason for this uncertainty is the lowness of the backfire rate with either material which made short-time tests under normal conditions inconclusive. Since the inadequacy of the short-time tests was not realized, incorrect conclusions were frequently drawn.

The solution again seems to be to test under such conditions as will give an easily countable backfire rate and then to extrapolate to normal conditions. Hence some tests were made under the authors' direction on iron and graphite anodes with sufficiently high-test voltage as to give a very large backfire rate. The small metal tank rectifier (Fig. 5) was used. One anode was of iron and the other of graphite and both were shielded in a similar manner. An arc was carried to one anode and test voltage applied to the other and the backfire

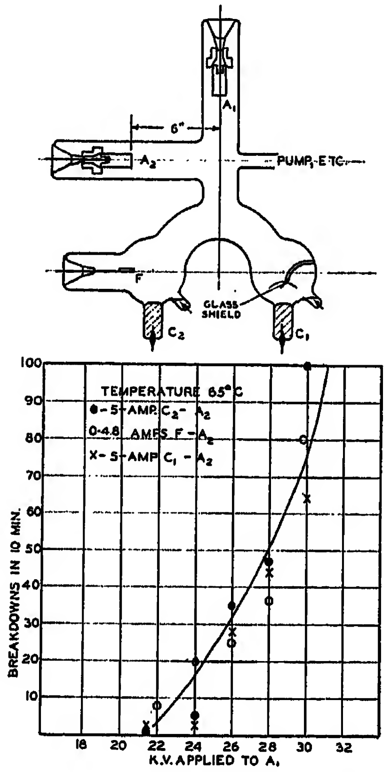


FIG. 7—RESULTS OF TESTS TO COMPARE BREAKDOWN RATE OF TUBE USING POOL *vs.* THERMIONIC CATHODE

rate counted. Then the arc was carried to the second anode and test voltage applied to the first. The results indicate that fewer causes of backfire appear with graphite, in a given period of time, but the difference is not greater than day to day variations with only one material.

From the standpoint of the tendency to backfire alone, the results are very clear. There is no great advantage of either material over the other. If the relative merits of graphite *vs.* iron anode keep this relationship when the voltage is lowered to normal, then an answer is obtained to a question which would require many years of observation on many rectifiers to determine under normal conditions.

Another example of the application of these ideas is in determining the relative merits of cathodes of thermionic type as compared with cathodes of the conventional mercury pool type generally used. In recent years thermionic cathodes have become available with suf-

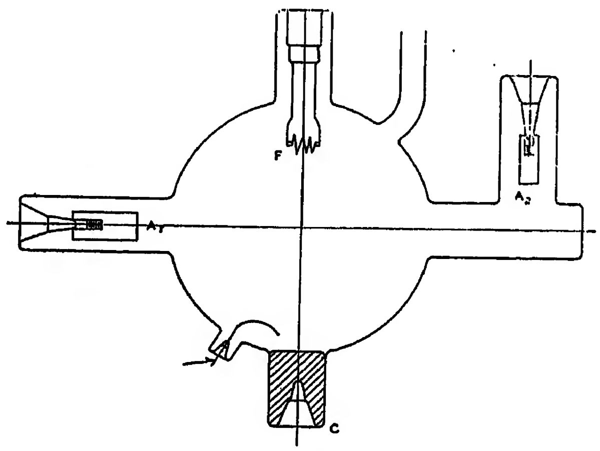


FIG. 8—SKETCH OF TUBE HAVING POOL AND THERMIONIC CATHODE, BUT COMPARATIVELY UNSHIELDED ANODE

ficient current capacity and sufficiently long life to make it possible to consider their use in power mercury arc rectifiers. It is certainly highly desirable therefore to determine whether thermionic cathodes have any great advantage over the pool type with respect to backfires. A glass tube was therefore constructed as shown in Fig. 7, containing both a thermionic cathode and a mercury pool cathode. An arc was run between each cathode and the anode A_1 and test voltage applied to A_2. The results obtained are shown in Fig. 7. There is apparently no difference in the backfire rate for the two kinds of cathode for this tube.

With another tube shown diagramatically in Fig. 8, quite different results are obtained as to the relative merits of thermionic *vs.* pool cathodes, as shown in the following table.

Arc current	Volts on A_1	Back current milliamperes	Breakdown rate
7.5 amp. F-A_2	6,000	2	0 in 10 min.
7.5 amp. C-A_2	6,000	1.5	5 in 10 min.
7.5 amp. F-A_2	8,000	4 – 6	29 in 10 min.
7.5 amp. C-A_2	8,000	2 ±	725 in 10 min.

The difference in performance of the tubes is probably due to differences in shielding of the anodes from exposure to the cathode. The thermionic cathode thus seems to possess the advantage that much less shielding is required with it.

Section VIII

Backfires Forbidden by Generally Accepted Theories

It is quite clear that in practical rectifiers there will be certain grosser causes of backfire which will not occur in the random way described in the previous sections. For example, a conducting deposit may form over the insulator between the tank and the anode. Such a conducting deposit may start an arc in the same way as a blowing fuse wire, when negative voltage is applied to the anode. Such deposits may be expected to develop in a more or less regular way with time, and will not therefore cause backfires which occur in a random manner. Conducting deposits of this kind and other grosser causes of backfire can be avoided by proper design and suitable maintenance of a rectifier.

We wish to leave out of further account such grosser backfire causes and to consider only the backfires that occur away from the insulator surfaces. Direct observation shows that in well constructed and treated rectifiers, backfires take place not over insulators nor at the junction of anodes with insulators, but directly at the anode surface which is carrying current to the mercury vapor.

According to present available theories of the cathode of an arc, backfire should never occur without some initiating circumstance which is foreign, not inherent, or not necessary to the kind of discharge which is taking place just before the backfire. An arc is to be distinguished from a glow in that only a low voltage less than 20 volts is required at the cathode for its maintenance. A glow on the other hand is a self-maintaining discharge which requires at least several hundred volts at the cathode.

In mercury arc rectifiers, generally the construction and vapor pressure is such that it is not possible to hold a self-maintaining glow with the available negative voltage which is impressed on the anode. However, with normal negative voltage on one anode and an arc playing to another anode, a current flows to the negative stressed anode in a discharge which does not differ in any essential way from a glow. This discharge differs from the glow only in not being self maintaining; that is, if the arc to the other anode is stopped, then this discharge stops, whereas if conditions are such as to permit a glow, then the glow continues even if the arc to the other anode is stopped. It is possible, as by increasing the vapor pressure, to change the discharge continuously from the non-self-maintaining form to the self-maintaining glow without any great discontinuity in appearance or properties of the discharge. In fact the only way to tell whether a self-maintaining glow has formed is to stop the arc current to the other anode and see whether the discharge stops. In what follows we shall make no distinction between a self-maintaining glow and the non-self-maintaining discharge, but shall refer to them both as the back-current discharge. The current in the back-current discharge is generally quite small, only a few milliamperes for the usual size anode in commercial rectifiers. The current is distributed over the anode surface rather uniformly. Shields, grids and in general any surfaces in proximity to the anode to which ions may discharge greatly lower the back current to the anode.

A backfire consists in the sudden substitution of an arc for the normal back-current discharge. Somehow the conditions for the maintenance of the cathode of an arc must suddenly set themselves up. The conditions required at the cathode of an arc as predicted by present theory are such as should not occur spontaneously so far as the intrinsic characteristics of the back-current discharge go. The conditions required at the cathode of an arc, according to present theories, call for either a very high temperature or a high-current density.[1]

If a temperature at some point of the cathode surface reaches a value sufficiently high for thermionic emission to take place to a considerable degree, then an arc may form. For graphite or iron this temperature is greater than 2,000 deg. cent., but with the low-current density in the back-current discharge it is impossible to obtain such a temperature so long as the current remains uniformly distributed.

Another circumstance which would start an arc is the development of a sufficiently intense electric field at the cathode surface which would draw electrons out even though the surface was cold. Such a field must have a magnitude of 1,000,000 volt per cm. or more. Clearly this field must be maintained by a large concentration of positive ions near the cathode surface and it turns out that the current density corresponding to any such large positive ion concentration must be several thousand amperes per sq. cm.[2] But the current density in the back-current discharge is only a few microamperes per sq. cm.

It might be thought that if sufficiently small areas of the cathode surface are considered, spontaneous variations in current density in the small areas would give rise to such values as would give either the intense field or the high temperature necessary for forming the cathode of an arc. For instance, if an area a little larger than the section of a single positive ion is considered, then the current density to it is zero most of the time and rises to enormously high values during the moment when a positive ion strikes it. However, it is not permissible to consider such small areas. Experiment shows that the cathode of an arc on electrodes of usual size is unstable when the current in the arc is less than 0.05 amperes[3] and that it will change spontaneously to the glow form of discharge. Therefore, we must consider areas sufficient to supply more than 0.05 amperes of arc current. With the current density of 5,000 amperes per sq. cm. such an area would need to exceed 10^{-5} sq. cm. As is shown in Appendix III,

1. For references see Bibliography.

fluctuations in the field intensity over such an area, due to fluctuations in the density of positive ions opposite the area, will cause field intensities of a magnitude sufficient for drawing out electrons so rarely as to fail utterly to account for the observed frequency of occurrence of backfires in rectifiers.

Scrutiny of the back-current discharge through the spectacles of the present theories of the cathode of an arc fails to reveal the causes of backfire, but in this scrutiny the cathode surface was regarded as being the homogeneous surface of a perfectly homogeneous solid. The possible influences of contaminations on the surface and flaws in the electrode material must then be considered. But before doing this, some interesting experiments carried out by D. E. Marshall are given below.

Section IX

Backfires Initiated by Particles Making or Breaking Contact

A tube was constructed as shown in Fig. 9. The electrodes were of graphite. Near the cathode was a glass plunger with a tungsten tip fused into it 0.075 centimeters in diameter, and 2 millimeters long. The plunger could be operated magnetically so as to strike the cathode, remain firmly in contact with the cathode, or be moved out of contact with the cathode. A small amount of liquid mercury was in the tube and the vapor pressure was controlled by placing the tube in an oil bath whose temperature could be varied.

Voltage was applied to the tube from a condenser which was charged from a transformer by means of a thermionic rectifier. When sufficiently high voltage was applied, a glow started in the tube which was quite stable and carried a small current and requiring the continued application of the high voltage. The glow was quite stable if the plunger did not touch the cathode and also when the plunger was firmly in contact with the cathode, but if the plunger was made to strike the cathode, at the moment of contact with the cathode there would be a flash and the condenser would be completely discharged, indicating that an arc had formed with a very large momentary current. Similarly at the moment of breaking contact with the cathode there was a backfire. Thus making or breaking contact of the cathode with a small piece of completely insulated tungsten wire will cause a backfire.

The cause of the backfire is to be sought in the very high-current density at the last contact point. Although the little piece of tungsten collects an exceedingly small back current, this back current must flow to the cathode through the last contact area. As the contact area shrinks to zero the small current collected by the tungsten wire gives a very high-current density at the last contact and a very rapid rise in temperature to a high value must take place there. There is undoubtedly an explosive volatilization of material there with a momentarily very high vapor density and this vapor probably is almost completely ionized. This would permit a high-current density to flow from the gas space to the electrode with enough total current to start a stable arc.

Marshall has also made tests showing that making or breaking of contact of cathode with small mercury drops will cause backfire. Contacting with good insulators, however, did not seem to cause backfire.

Section X

Causes of Backfires

The preceding section suggests a host of possible causes of backfires. A very obvious one is contacting mercury drops thrown from the pool cathode. Proper shielding of the anodes should almost completely eliminate this cause for backfire, but it is possible that occasionally a small droplet subject to Brownian

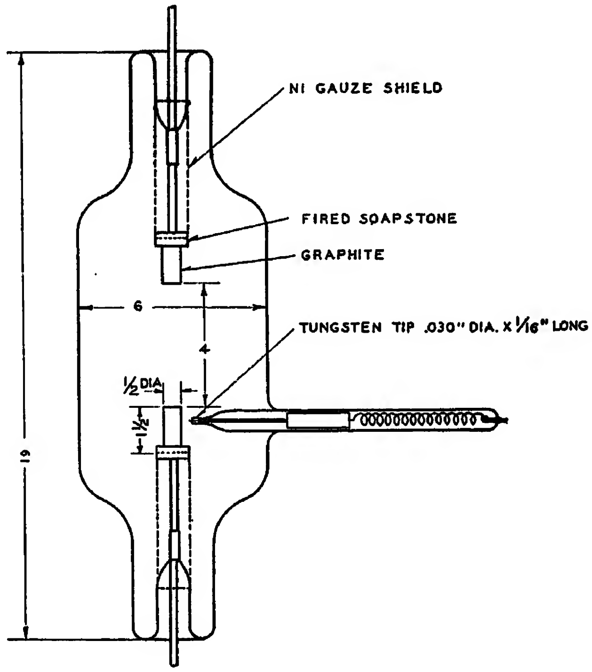


Fig. 9—Glass Tube with Tungsten Point to Contact with One Electrode

movement may reach the anode in spite of the shield. Small conducting particles of any metal carried around by the mercury vapor streams may contact with the anode and cause backfire, as, for example, a small piece of iron rust or scale. This is an argument for the greatest care in cleanliness in assembly of rectifiers.

Particles may detach themselves from the anode itself. It is well known that under the influence of the back current the anode suffers a very slow disintegration and loss of material known as sputtering. While the sputtered particles may consist in large part of individual molecules, it is believed that larger particles are also detached,[4] although they may be subsequently volatilized in the discharge itself. When a sufficiently large particle detaches itself a backfire may occur. Irregularities in the size of sputtered particles may

perhaps be expected to occur spontaneously even in the absence of any impurities on the electrode surface or in the electrode material. However, the presence of such impurities should tend to greatly increase the irregularity of sputtering and make the detachment of large particles more frequent. Thus if there is a small amount of gas in the metal the distribution of this gas should not be expected to be a uniform one, but subject to considerable fluctuations in local density due to the smallness of the actual gas content so that a small area of the electrode may be momentarily rich in gas and in such a state that a large particle may be detached. This suggests that advantage is obtained by removing gas from the electrodes as thoroughly as possible.

It may not be necessary for a large particle to completely detach itself from the electrode. If the particle makes poor thermal contact with the electrodes, then under the influence of the back current it may be raised to a high temperature in spite of the low-energy input density and a backfire may be started.

From this discussion on possible backfire causes it would be expected that the magnitude of the back current is important. If the back current is large, then the particle size necessary to cause backfire will be smaller and particles of such size will occur more frequently. If the back current is large, the sputtering of the electrode will be more rapid and large particles are more likely to be detached or loosened. Any means which reduces the back current to the electrode such as grids, shields, etc., must also reduce the frequency of occurrence of backfire and experience shows this to be the case.

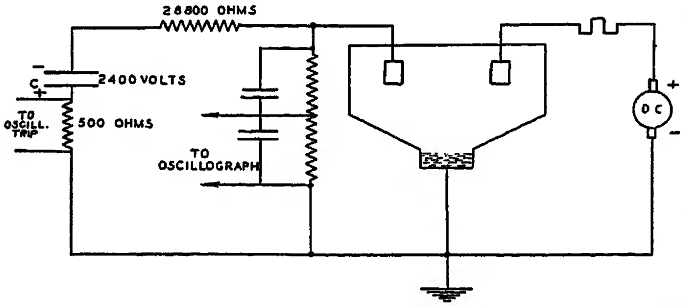


Fig. 10—Cathode-Ray Oscillograph Circuit

Another cause of backfire suggested by Langmuir[5] is the formation of insulating patches on the electrode with dielectric failure of the patch as it gets charged up by back current. These patches are made up of impurities, oxides, or what not and because of the small amount of material in their make-up their development to large sizes will be a random occurrence. Other experimenters also have surmised the existence of such insulating layers.[9]

Section XI

Duration of Backfire Causes

The random manner of occurrence of backfire as well as considerations of the preceding section make us believe that backfire causes involve only a small amount of matter. Since the amount of matter involved is very small, we should expect also that the time involved by backfire cause would be very small. This is verified by a cathode-ray oscillograph study made by F. A. Maxfield.

The cathode-ray oscillograph was of the type developed for lightning investigation and has been described elsewhere.[6] The circuit used is illustrated in Fig. 10, the Norinder relay functioning to cause the oscillogram to be taken immediately after the starting of a randomly occurring backfire. The small two-anode metal tank was used. An arc of 75 amperes flowed to one anode and 2,400 volts were applied to the other by a charged condenser. In series between this condenser and the anode under test a resistor of 28,800 ohms was placed. The purpose of this resistor was to keep the current too low to maintain an arc even though the backfire cause made the voltage from anode to cathode fall to a low value. Thus it was expected that the voltage on the tested anode which would fall to the low value during the existence of the backfire cause would return to normal when the backfire cause ceased.

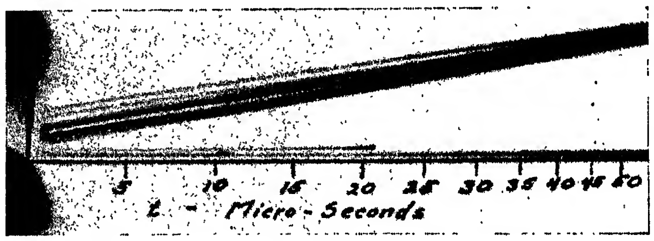


Fig. 11

Fig. 12

Figs. 11 and 12—Cathode-Ray Oscillograms Showing Time Duration of Backfire Causes

Oscillograms of the voltage across the tested anode are shown in Figs. 11 and 12. The recovery of normal voltage began to take place in an exceedingly short time, usually less than 5 microseconds from the time the backfire cause started. The finite slope of the recovery curves shown in the figures is due to the electrostatic capacity of the potentiometer by which the oscillograph was connected to the rectifier. The initial drop in voltage upon the occurrence of the back-

fire cause does not appear upon the oscillograms because of the slight lag in operation of the Norinder relay circuit. A check of this circuit showed that the delay was less than 3 microseconds so that the whole duration of backfire cause was less than 5 microseconds. Out of 500 oscillograms taken with this arrangement, only one backfire cause was found to be of long time duration. It appears in Fig. 12 as a line which is practically horizontal and represents low voltage for the duration of the film. This particular backfire may have been a failure over the insulator surface.

Section XII

Transition from Glow to Arc

The transition from glow to arc is of great theoretical interest and has been studied by physicists apart from its application to mercury arc rectifiers. Many believe that the transition is continuous; namely, that as the current density is increased in the glow, the voltage will stop increasing and will decrease continuously down to arc voltages. This has been established experimentally for tungsten electrodes under circumstances where the glow could heat the tungsten up to temperatures sufficient for thermionic emission.[7, 10]

But for non-refractory electrodes or electrodes under such circumstances that they cannot reach temperature for thermionic emission under the glow conditions applying up to the moment of experimentally observed transition, it is hard to explain a continuous transition since the transition occurs while the glow current density is very far less than that corresponding to an arc. Furthermore, the transitions appear to occur in an erratic or random manner which is not compatible with the idea of a continuous transition.

A continuous transition was believed to have been observed by Schrum and Wiest[8] with a copper cathode in air at atmospheric pressure. However, since backfire causes may be of such short duration and may occur with very great rapidity, it is possible that the continuous transition believed to have been observed by these investigators was really a rapid alternation from regular glow to a low-voltage discharge maintained by a backfire cause, the frequency of alternation being beyond the capacity of the oscillograph used to follow.

The transition is frequently attributed to a speck of impurity on the cathode, having a lower thermionic work function, that is, electron emission at a lower temperature than the other cathode material. This idea is in better accord with the random occurrence of the transition since these specks are thought of as being of an accidental origin. However, it is just as hard to account for the transition on a cathode of low work function as on one of high, if, as is usually the case, the energy in the glow is insufficient to raise the cathode temperature by an appreciable amount. It seems to the authors that more important than low work function at the speck is poor thermal or electrical contact of the small particle with the cathode and that transition may occur discontinuously and at random even with electrodes of the highest degree of purity and due entirely to irregularities in the manner of sputtering.

Section XIII

Conclusion

1. Backfires in mercury arc rectifiers are inherently random phenomena. There are no fundamental limitations of the rectifying process beyond which backfires may be said to occur, and within which they may be said not to occur.

2. The proper appreciation of the nature of backfire requires that the quality of a rectifier be determined and expressed in terms of its probability to backfire, or its average rate of backfire. Clearly the present methods of testing rectifiers at both full load and overload are insufficient to determine its true quality.

3. Research, and the development of mercury arc rectifiers may be greatly aided by the use of means for producing backfires at an abnormally large rate, so that the mean frequency of backfire can be determined in a reasonable length of time.

4. The idea of random backfire agrees very well with the random way in which backfire causes would be expected to take place, based on the best present knowledge of what these causes may be.

5. The duration of these backfire causes is very short, usually less than 3 microseconds. This indicates a very small amount of material involved in the formation of a cathode spot, on an anode.

6. The transition from glow to arc in the mercury arc rectifier is also found to take place in a random manner, and since this fact is incompatible with a continuous transition, the transition must be accepted as discontinuous.

Appendix I

During a long period of testing of a mercury arc rectifier, a number of time intervals between successive backfires will be observed. If the backfires take place in a random manner, what percentage of these intervals will exceed a given time t? Let m be the number of intervals which exceed the time t, and then $\frac{m}{M}$ will be the fraction of the total exceeding the time t.

To find $\frac{m}{M}$, we must know the probability of backfire per unit time, which is p. The probability of backfire in the time t is $p\,t$. Now suppose that this time t is divided into a large number of subintervals Δt. The chance of having a backfire during anyone of these subintervals is $p\,\Delta t$. The chance of not having a backfire during the first subinterval, Δt_1 is therefore $(1 - p\,\Delta t_1)$. The chance of not having a backfire during the first two consecutive subintervals is

$$(1 - p\,\Delta t_1)\;(1 - p\,\Delta t_2)$$

The chance of having no backfire during the first q consecutive subintervals is

$$(1 - p \Delta t_1)\ (1 - p \Delta t_2) \ldots (1 - p \Delta t q)$$

If we make the subintervals equal to each other,

$$(1 - p \Delta t)^q$$

is the chance of having no backfire during the first q subintervals. In the time t, there are $\frac{t}{\Delta t}$ subintervals and therefore:

$$\frac{m}{M} = \lim_{\Delta t \to 0} (1 - p \Delta t)^{\frac{t}{\Delta t}} \quad (1)$$

To evaluate this expression as Δt approaches zero, it may be expanded. Then,

$$(1 - p \Delta t)^{\frac{t}{\Delta t}} = 1 - \frac{t}{\Delta t} p \Delta t + \frac{\frac{t}{\Delta t}\left(\frac{t}{\Delta t} - 1\right)}{2\,!} p^2 (\Delta t)^2 - (\ldots.) + (\ldots.) \ldots. \quad (2)$$

As Δt approaches zero, (2) becomes

$$\lim_{\Delta t \to 0} (1 - p \Delta t)^{\frac{t}{\Delta t}} = 1 - p t + \frac{(p t)^2}{2\,!} - \frac{(p t)^3}{3\,!} + \ldots \quad (3)$$

But

$$e^{-pt} = 1 - p t + \frac{(p t)^2}{2\,!} - \frac{(p t)^3}{3\,!} + \ldots \quad (4)$$

Hence

$$\frac{m}{M} = \epsilon^{-pt} \quad (5)$$

This expression may also be obtained by solving the differential equation

$$\frac{d m}{d t} = - m p \quad (6)$$

and using the terminal condition that

$$m = M \quad \text{when} \quad t = 0 \quad (7)$$

Appendix II

Suppose that a large number of rectifiers N is tested, and that it is known that the probability of backfire of each is p per unit time. If the rectifiers are tested for unit time, what percentage of them will be expected to give no backfires? This percentage may be found by substituting in equation (5). For example let p = one per month, and let t = one month. Then,

$$\frac{n}{N} = \frac{1}{e} = \frac{100}{e} \% = 36.7\% \quad (8)$$

During this test, how many rectifiers will be expected to backfire exactly once? Let R be the number of rectifiers which, at a time t, have backfired exactly once. Then,

$$d R = n p d t - R p d t \quad (9)$$

and

$$\frac{d R}{d t} + R p = p N e^{-pt} \quad (10)$$

if for n, its value from equation (5) is substituted. Solving the equation (10)

$$R = p N t e^{-pt} + K e^{-pt} \quad (11)$$

in which K is a constant of integration. The terminal condition is

$$R = 0 \text{ when } t = 0 \quad (12)$$

Substituting this condition, and using the value found for K;

$$R = p N t e^{-pt} \quad (13)$$

or the fraction $\frac{R}{N}$ which will backfire exactly once during the test is

$$\frac{R}{N} = p t e^{-pt} \quad (14)$$

Again using the numerical values $p = 1$ and $t = 1$;

$$\frac{R}{N} = \frac{1}{e} = \frac{100}{e} \% = 36.7\% \quad (15)$$

Thus if 36.7 per cent do not backfire at all, and 36.7 backfire once, during a test of one month,

$$100\% - 36.7\% - 36.7\% = 26.8\%$$

will backfire twice or more during the test.

Appendix III

FLUCTUATIONS IN THE GRADIENT AT THE SURFACE OF AN ANODE

The average gradient at the surface of an anode during the period of back voltage may be calculated from Poisson's equation, upon the assumption that the positive ion current to the anode is limited by space charge. If the initial velocity of the positive ions at the boundary of the space charge sheath is neglected, if the ions make no collisions within the sheath, and if the anode is considered a plane, the current, voltage, and gradient relations at the anode surface are,

$$i = \frac{5.45 \times 10^{-8}\, V^{3/2}}{\sqrt{M_0}\, d^2} \quad (1)$$

$$\frac{\partial V}{\partial x} = \frac{4}{3} \frac{V}{d} = 5.7 \times 10^3\, M_0^{1/4}\, V^{1/4}\, i^{1/2} \quad (2)$$

where d is the space charge sheath thickness in centimeters, i is the positive ion current density in amperes per cm.^{2}, V is the anode potential in volts, and M_0 is the molecular weight of the ions.

The average gradient at the anode is also given by

$$\frac{\partial V}{\partial x} = 4\,\pi\,N\,e \qquad (2a)$$

where N is the total number of positive ions in the space charge sheath opposite one cm.^{2} of the anode surface. Then random fluctuations in the number of ions in the space charge sheath opposite an element of area ΔA will cause fluctuations in the gradient over ΔA. What is the probability that the average gradient will be multiplied by a factor ρ, sufficient for high-field electron emission to occur?

According to Poisson's Law,[11] which will apply in this case with sufficient accuracy, the probability of n ions occurring over an interval ΔA, where the expected number of ions is $N\,\Delta\,A$, will be

$$P\,(n) = \frac{(N\,\Delta\,A)^n}{N\,!}\,\epsilon^{-N\Delta A} \qquad (3)$$

In order that a field of the desired magnitude exist, $n = \rho\,N\,\Delta\,A$. For purposes of calculation $N\,!$ may be evaluated by Stirling's formula

$$N\,! = \sqrt{2\,\pi\,n}\,n^n\,\epsilon^{-n} \qquad (4)$$

Making these substitutions, the probability of a field high enough for electron emission occurring over any area $\Delta\,A$ is

$$P = \frac{\epsilon^{(\rho-1)N\Delta A}}{(2\,\pi\,\rho\,N\,\Delta\,A)^{1/2}\,\rho^{\rho N\Delta A}} \qquad (5)$$

Of course, actually the distribution of positive ions is continually changing; but a good idea of the fluctuations may be obtained if it is considered that any configuration of positive ions endures for a time $\Delta\,t$, then suddenly changes to a different configuration. $\Delta\,t$ is made equal to the time of transit of a positive ion across the space charge sheath. Thus, the number of occurrences per second, over the entire anode, favorable for the development of a backfire is

$$\nu = \frac{A}{\Delta\,A}\,P\,\frac{1}{\Delta\,t} \qquad (6)$$

$\Delta\,t$ may be calculated, on the basis of the assumptions used previously, from

$$M\,\frac{d^2\,x}{d\,t^2} = e\,\frac{d\,V}{d\,x} \qquad (7)$$

$$\frac{d\,V}{d\,x} = \frac{4}{3}\,\frac{(9\,\pi)^{2/3}}{\left(\dfrac{2\,e}{M}\right)^{1/3}}\,i^{2/3}\,x^{1/3} \qquad (8)$$

So,

$$\frac{d^2\,x}{d\,t^2} = 6\,(2/3\,\pi)^{2/3}\left(\frac{e}{M}\right)^{2/3} i^{2/3}\,x^{1/3} \qquad (9)$$

Integrating twice

$$x^{1/3} = \left(\frac{2}{3}\,\pi\right)^{1/3}\left(\frac{e}{M}\right)^{1/3} i^{1/3}\,t \qquad (10)$$

Thus,

$$\Delta\,t = \frac{d^{1/3}}{(2/3\,\pi)^{1/3}\left(\dfrac{e}{M}\right)^{1/3} i^{1/3}}$$

or, putting in numerical values, and substituting from (1)

$$\Delta\,t = 5 \times 10^{-10}\,\frac{M_0^{1/4}\,V^{1/4}}{i^{1/2}} \qquad (11)$$

As typical data, the following may be taken:

Peak Anode voltage	=	1,600 volts
Anode current	=	10 milliamperes
Anode area	=	625 cm.^{2}
Current density	=	1.6×10^{-5} amperes per cm.^{2}

For mercury, $M_0 = 200$. So, from equation (2), at the anode surface

$$\frac{\partial V}{\partial x} = 545 \text{ volts per cm.}$$

In order for an appreciable number of electrons to be emitted from cold metals, theory indicates that a field of 5×10^7 volts per cm. is needed. It is hardly conceivable that surface irregularities can multiply the field by more than a factor of 100. So, at least a field of 5×10^5 volts per cm. must result from random fluctuations before backfire can occur from this cause. The value of ρ then is 1,000.

The value of N, from equation (2a), is 3×10^8, while from equation (11), $\Delta\,t$ comes out 3×10^{-6}.

In order to make the probability come out as large as possible, we shall assume that an anode bears the peak inverse voltage continually. From equations (6) and (5) the average number of backfires to expect per second per anode due to fluctuations in the field, will be

$$\nu = \frac{625}{\Delta\,A}\,\frac{\epsilon^{999 \times 3 \times 10^8 \Delta A}}{(2\,\pi \times 1000 \times 3 \times 10^8\,\Delta\,A)^{1/2}\,1000^{1000 \times 3 \times 10^8 \Delta A}}\,\frac{1}{3 \times 10^{-6}}$$

If we take $\Delta\,A = 10^{-5}$, which seems to be a reasonable figure, approximately

$$\nu = 4.78 \times 10^4\,\epsilon^{2.997 \times 10^6}\,1000^{-3 \times 10^6} = 10^{-7.7 \times 10^6}$$

Thus, the average time between backfires, on this hypothesis, would approach $10^{7,700,000}$ years.

Suppose $\Delta\,A$ is made 3.3×10^{-9}, so that $N\,\Delta\,A = 1$. Then,

$$\nu = 7.87 \times 10^{14}\,\epsilon^{999}\,1000^{-1000}$$
$$\sim 10^{-2551}$$

The average time between backfires would be about 10^{2554} years.

From these calculations, it seems impossible that

fluctuations in the electric field at the anode surface, due to fluctuations in positive ion density alone, can account for backfires in practical rectifiers.

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Overvoltage on Transmission Systems Caused by Dropping Load

Discussion of Means of Limiting Such Overvoltage with Particular Reference to the Use of Generator Voltage Regulators

BY E. J. BURNHAM*
Associate, A. I. E. E.

***Synopsis.**—In a previous article[1] the author showed the manner in which under different conditions the voltage on transmission systems will rise due to the dropping of load, and described some means of limiting the voltage rise to avoid overstressing insulation. This paper describes further means of limiting the voltage under such conditions, considering first an improved type of regulator and wheatstone bridge main exciter field rheostat and second, as an alternative, a method of automatically inserting resistance in the alternator field circuit. Tests are described which show the effectiveness of these methods of limiting the voltage.*

INTRODUCTION

It is generally understood that total or partial loss of load on waterwheel driven generators or hydro stations frequently results in undesirable voltage rise, and that in such cases it is desirable to limit the voltage rise to avoid overstressing the insulation of generators and connected apparatus.[1]

In the past this has sometimes been accomplished by use of overvoltage, overspeed or overfrequency relays which automatically open the field circuit and trip the generator from the line or bus when the voltage or speed reaches a predetermined value. This is a very effective way of limiting the overvoltage, but it has a disadvantage if several units are in the station because after the machines are separated, considerable time is lost resynchronizing the units and getting them back in service.

It has long been recognized that generator voltage regulators are beneficial in reducing the generator voltage at times when load is lost, but with the older type of excitation systems and regulators which insert a series block of resistance in the main exciter field circuit, the voltage reduction which could be produced often was not adequate either in magnitude or promptness. However, with improved voltage regulators and the use of excitation systems as now developed, it is possible to hold the generator voltage within desired limits when load is dropped.

The purpose of this paper is to show how the voltage on a waterwheel generator or hydro station may be held within reasonable limits at a time when full load is suddenly lost without opening the field circuits of the machines and tripping them from the line or bus.

Tests made on a 47,000-kva. generator at the Spier Falls Plant of the New York Power and Light Corporation are described in which use was made of a newly developed generator voltage regulator and a wheatstone bridge type of main exciter field rheostat, making it possible to reduce quickly the generator field current and thereby limit the generator voltage.

Tests made on the same generator are also described showing the possibilities of limiting generator voltage by inserting resistance automatically in the alternator field.

It is often desirable to determine the overvoltage characteristics of a generator or station under different conditions before the station is built or completed in order that suitable precautions can be taken in the design period. For this reason a method of calculation is included in the appendix, the results of which check very closely with tests.

TEST CONNECTIONS

Fig. 1 shows a simplified diagram of connections used in the tests taken at the Spier Falls Station. The generator is rated 47,000 kva., 81.8 r. p. m., 60 cycles, 13,800 volts, 0.80 power factor, and the direct-connected main exciter, 264 kw., 250 volts. The field of the main exciter is excited from a 6-kw., 250-volt, compound-wound direct-connected pilot exciter. The main exciter is compound wound, but, as tests were desired for a shunt-wound exciter, arrangements were made to insert, by use of a switch, an 0.08-ohm resistor in the alternator field circuit, which would change the time constant of the circuit to a value that would simulate that of a shunt-wound main exciter.

The generator is connected to the 110-kv. bus through a bank of transformers rated 47,000 kva. There being no low-voltage bus or circuit breaker, load was always dropped in the tests, by tripping the high-voltage transformer circuit breaker.

A six-element oscillograph was used on which the following currents and voltages were recorded:

1. 60-cycle timing wave.

*General Electric Company, Schenectady, N. Y.

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Presented at the South West District Meeting of the A. I. E. E., Kansas City, Mo., October 22-24, 1931.

2. Alternator armature current.
3. Main exciter field voltage.
4. Alternator armature voltage.
5. Main exciter armature voltage.
6. Alternator field current.

Regulator Equipment

The main control element of the regulator known as the FA-4 is shown in Fig. 2 and the high-speed relays X and Y in Fig. 3.

The regulator may be used with a wheatstone bridge main exciter field rheostat as shown in the diagram, or with a series type rheostat.

The wheatstone bridge rheostat, Fig. 1, is suitable for use with synchronous condensers or other machines where the excitation range is broad and it is desirable to reduce the main exciter voltage to a very low value or reverse it, or where it is desirable to reduce the exciter

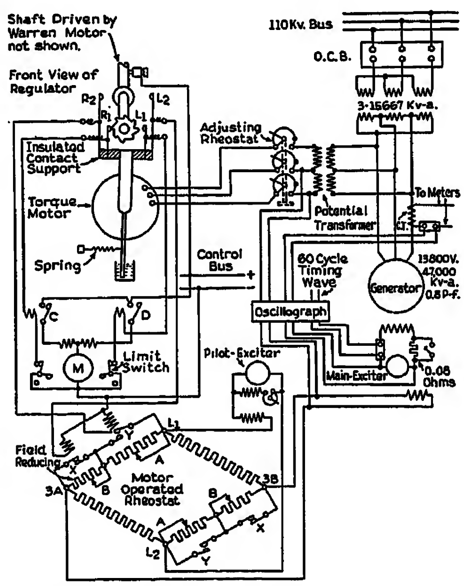

Fig. 1—Diagram of Connections for Tests at Spier Falls Station

voltage very quickly as in the case under consideration.

Arms marked A are operated simultaneously by motor M. The arms marked B are operated simultaneously by handwheel and are used for adjustment to give the desired voltage reduction when the high-speed relays X open. In the case under consideration a setting was made such that when relays X opened the main exciter armature voltage was reduced to a negative value of approximately 10 volts.

The primary control element of the FA-4 regulator consists of a three-phase torque motor to the rotor of which are attached two pairs of contacts. Both front and rear contacts make contact with disks connected to a shaft driven at constant speed by a small a-c. motor. The front disk has cam-shaped teeth while the rear disk is smooth.

Secured to the shaft of the torque motor is an arm to which is attached a spring which balances the torque of the torque motor. The arm also carries a paddle which is immersed in a vessel of oil, producing the required damping action.

Operation of Regulating Equipment

This regulator remains inoperative with both pairs of contacts out of engagement as long as no change in excitation is required. For slight changes in voltage

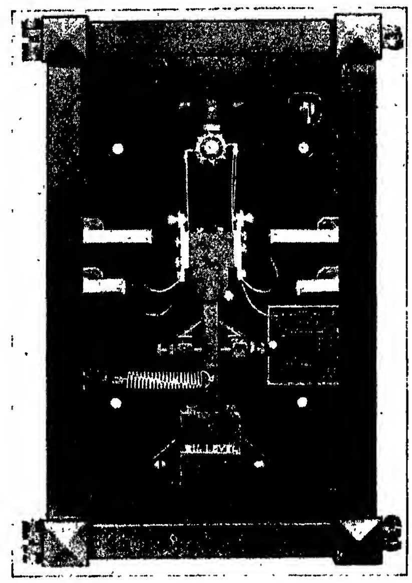

Fig. 2—Front View, Type FA-4 Regulator

only the front contacts $L\,1$ and $R\,1$ and the motor-operated field rheostat are affected, the action being a "notching" one varying from a single brief impulse to practically continuous operation of the motor, depending upon the correction required. Only for greater

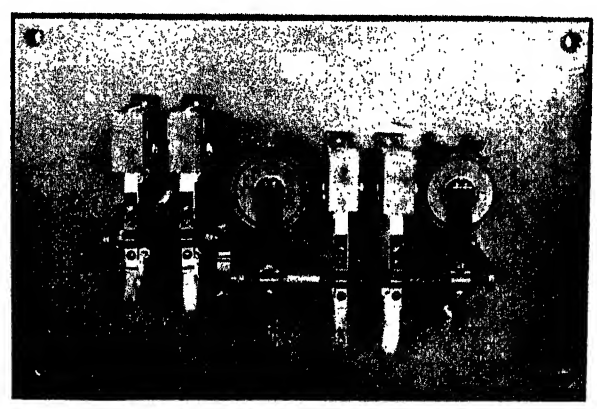

Fig. 3—High-Speed Relays for Use with FA-4 Regulator

changes in voltage do the back contacts $L\,2$ and $R\,2$ and the high-speed relays come into action maintaining the voltage until the motor-operated rheostat has moved to a position corresponding to the required excitation.

The notching action of the front contacts in conjunction with the intermittent operation of the rheostat prevents over-travel of the latter and consequent hunting. On voltage changes of greater magnitude

the periods of engagement of the front contacts are longer, tending to move the motor-operated field rheostat more rapidly.

The back contacts go in operation when the a-c. voltage has changed 3 to 15 per cent according to the adjustment made. The frequency range under which the regulator will hold constant voltage is very broad being between the limits of 25 and 85 cycles.

Equipment to Insert Resistance Automatically in the Alternator Field Circuit

Fig. 4 shows the diagram of connections and devices used to insert resistance automatically in the alternator

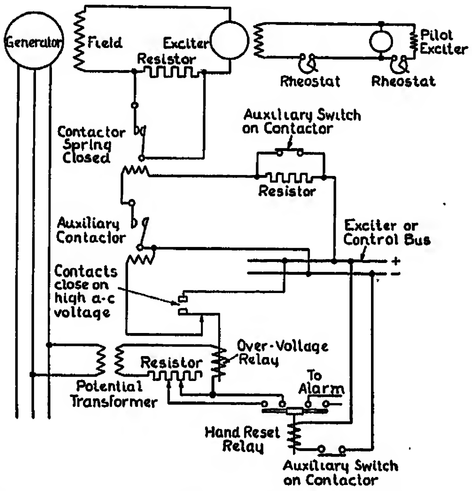

Fig. 4—Diagram Showing Method of Automatically Inserting Resistance in Alternator Field Circuit Upon Occurrence of Overvoltage

field circuit upon the occurrence of overvoltage. The overvoltage relay, which is of the contact making voltmeter type, endeavors to hold alternating voltage in accordance with its setting by opening and closing a contactor connected across a resistor in the alternator field circuit. In the case under consideration the overvoltage relay was set to operate at approximately 16,800 volts or 22 per cent over normal voltage. As soon as the contactor opens, the setting of the overvoltage relay may be changed if desired to hold normal voltage or a voltage of some predetermined value. This change in setting of the overvoltage relay is accomplished by the use of a hand reset relay which upon closing its contacts, changes the value of resistance in the coil circuit of the overvoltage relay.

Tests

An outline of the tests which were made is given in Table I.

Fig. 5 shows four tests which were taken at no load to compare the rate of decay of alternator voltage when the excitation was reduced in different ways. In each of the four cases, the alternator voltage was raised under hand control to approximately 16.1 kv. In case 1 the excitation was reduced by inserting a 20-ohm resistor in the main exciter field circuit corresponding to the value of field reducing resistance described later under load tests when regulator and series type main exciter field rheostat connections were used. In cases 2 and 3 the relays X in the wheatstone bridge circuit

TABLE I

Fig.	Main exciter	Type main exciter field rheostat	Load dropped kw.	Load dropped kva.	Power factor
5	Compound	Series	Tests taken at no load to compare rate of alternating voltage decay.		
5	Compound	Wheatstone Bridge			
5	Shunt	Wheatstone Bridge			
5	Insert resistor in alternator field circuit				
6	Shunt	Wheatstone Bridge	40,000	44,444	0.9
7	Compound	Wheatstone Bridge	40,000	44,444	0.9
8	Compound	Series	0	40,000	0
9	Compound	Wheatstone Bridge	0	40,000	0
10	Insert resistor in alternator field circuit		40,000	44,444	0.9

were opened. In case 4 the contacts of the overvoltage relay were closed, which inserted the 1.12-ohm resistor in the alternator field.

Figs. 6, 7, 8, 9 and 10 show the results of dropping load on the 47,000-kva. generator under different conditions.

Discussion of Test Results

Referring to Fig. 5, the voltage reduction produced with the wheatstone bridge was very rapid as compared

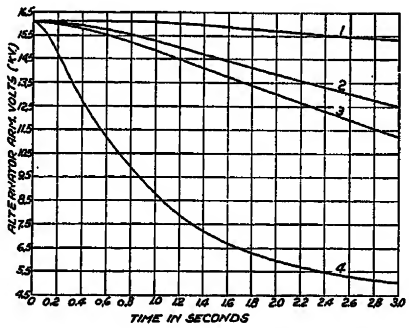

Fig. 5—Decrease of Alternator Open-Circuit Voltage

Case 1—By inserting series resistance 20 ohms in main exciter field. Compound exciter

Case 2—By opening relays x in wheatstone bridge circuit. Compound exciter

Case 3—By opening relays x in wheatstone bridge circuit. Shunt exciter

Case 4—By closing overvoltage relay contacts which inserted 1.12-ohm resistor in alternator field circuit

with that resulting from the insertion of series resistance in the main exciter field circuit, but not as rapid as the voltage reduction produced by inserting resistance in the alternator field circuit. Comparing cases 2 and 3, a more rapid voltage reduction was given by the shunt than by the compound arrangement of main exciter.

When load was dropped, there were two or three cycles of single-phase operation caused by the three poles of the 110-kv. circuit breaker not opening at exactly the same time. Because of this it will be

noticed, that the alternator field current did not decrease instantaneously at zero time, but instead dropped to its new value in about three cycles, which is reasonable when it is considered that it took that time to completely drop the load.

In all cases where 40,000-kw. load was dropped, a maximum speed of 138 per cent of normal was reached

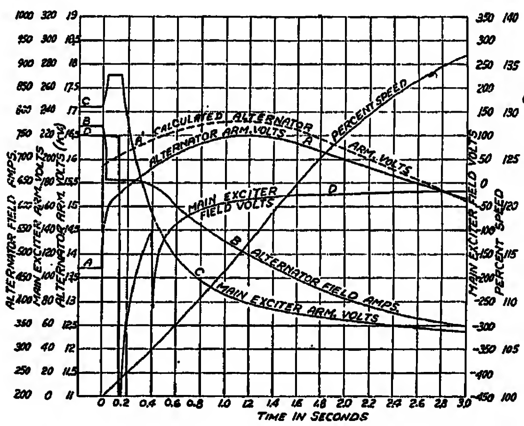

Fig 6—40,000-Kw. 0.9-Power Factor Load Dropped Using Wheatstone Bridge Rheostat. Shunt Exciter

in approximately 3.5 seconds. This is about the value expected and falls within general practise as shown by general overspeed curves given in Fig. 12.

Referring to Figs. 6 and 7, approximately 4 per cent higher alternator voltage was obtained with the compound than with the shunt-connected main exciter when a 40,000-kw. load was tripped using the wheatstone bridge arrangement. Also with the shunt exciter the

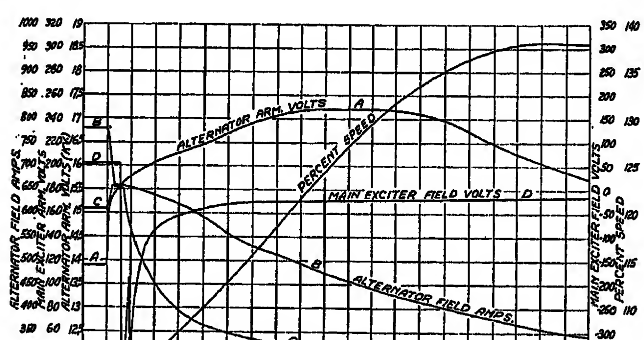

Fig. 7—40,000-Kw. 0.9-Power Factor Load Dropped Using Wheatstone Bridge Rheostat. Compound Exciter

overvoltage was reduced more quickly than was the case with the compound exciter. The maximum voltage when using the shunt exciter was 16.5 kv. or approximately 20 per cent above normal; and for the compound exciter 17.2 kv. or approximately 25 per cent above normal. This shows very clearly the effectiveness of the regulator with the wheatstone bridge arrangement because with no regulator the alternator voltage would have reached 180 per cent of normal value when tripping the high-voltage transformer circuit breaker and dropping 40,000-kw., 0.9-power-factor load. Without the effect of transformer magnetizing current as would be the case if the load was tripped on the low-voltage side of the transformer, the alternator voltage would reach double value with no regulator or voltage limiting means.

Figs. 8 and 9 show the results of dropping a 40,000-kva. entirely reactive load. These two tests give the

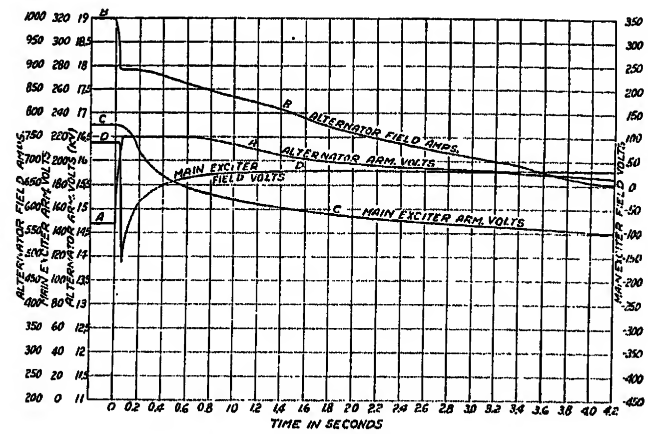

Fig. 8—40,000-Kva. Reactive Load Dropped Using Regulator and Series Rheostat. Compound Exciter

combined effect of generator regulation and regulator action without the effect of overspeed.

Referring again to Figs. 8 and 9, a comparison can be made between the effect of the regulator used with an ordinary series rheostat and used with a wheatstone bridge rheostat in the main exciter field. With the

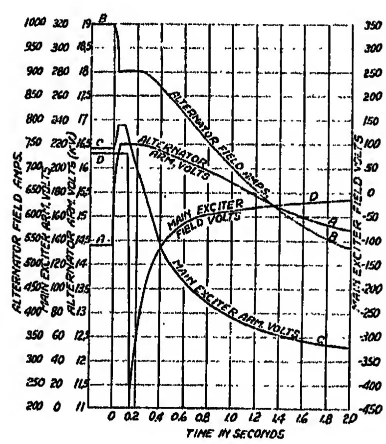

Fig. 9—40,000-Kva. Reactive Load Dropped Using Regulator and Wheatstone Bridge Rheostat. Compound Exciter

wheatstone bridge arrangement there was, in the first second after load was dropped, a change of alternator voltage of 575 volts, while with the series resistance connection the change was only 150 volts.

Fig. 10 shows what may be accomplished in limiting alternator voltage by automatically inserting resistance

of 1.12 ohms in the alternator field circuit when dropping a 40,000-kw., 0.9-power-factor load. In this test the overvoltage relay shown in Fig. 4 was set to operate at 16,800 kv., and hold this value. It will be noticed that the maximum alternator voltage reached was 17.7 kv. or approximately 128 per cent of normal. In attempting to hold the alternating voltage, the overvoltage relay opened and closed the contactor connected

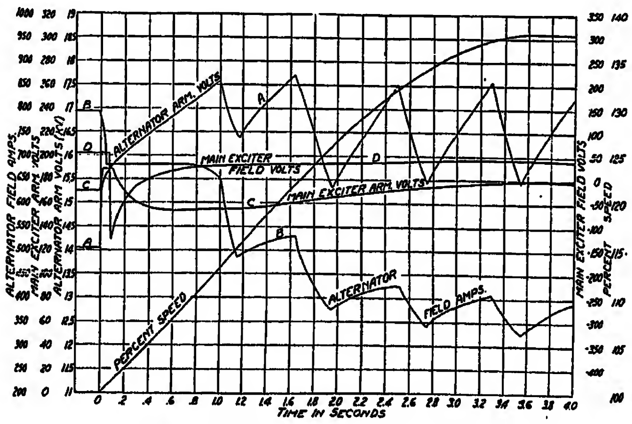

FIG. 10—40,000-KW. LOAD DROPPED. OVERVOLTAGE RELAY INSERTS RESISTANCE IN ALTERNATOR FIELD CIRCUIT. REGULATOR WITH SERIES RHEOSTAT IN SERVICE

across the 1.12-ohm resistor in the alternator field circuit, giving the sudden increases and decreases in alternator voltage. This operation continued until the regulator could get control and lower the alternating voltage to a point where the overvoltage relay would not operate. This was accomplished at the end of approximately 10 seconds, as shown by the high-speed voltage chart record given in Fig. 11. At this point the regulator which had been doing all it could to reduce the

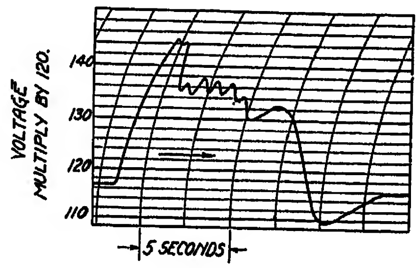

FIG. 11—HIGH-SPEED VOLTAGE CHART RECORD OF TEST SHOWN IN FIG. 10 WHERE RESISTANCE WAS AUTOMATICALLY INSERTED IN ALTERNATOR FIELD CIRCUIT

excitation, finally gained control and brought the voltage back to normal, the latter being reached in about 15 seconds. Note that the rather long time which elapsed before the regulator gained control was due to the use of the series instead of the wheatstone bridge arrangement. The voltage chart curve did not follow the oscillograph voltage curve very closely because of the damping action of the voltage chart pen.

CONCLUSIONS

The tests described indicate that a simple means of limiting overvoltage caused by dropping load is available, consisting of a suitable regulator and wheatstone bridge exciter field rheostat set to give zero or slightly negative main exciter armature voltage.

Such equipment under ordinary conditions functions as required to hold normal alternating voltage, but at the same time is ready to prevent the voltage from reaching dangerous values which would overstress the insulation of generators and connected apparatus. Furthermore, the use of such equipment has made it possible to design lightning arresters and protective apparatus to give better protection and at the same time not be subject to failure on over-dynamic voltage.

The alternative method of automatically inserting resistance in the alternator field circuit is also very effective in keeping the alternating voltage within desired limits when load is lost. Therefore this method is available for use where overvoltage protection is needed and there are no generator voltage regulators or where regulators are being used, but the excitation

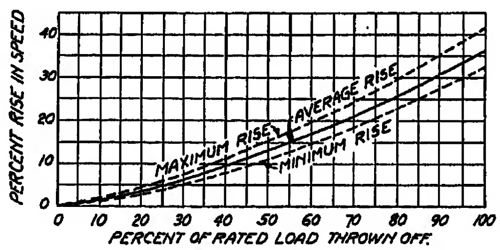

FIG. 12—TYPICAL SPEED CHANGES ON HYDRAULIC TURBINES FOR LOAD THROWN OFF TO ZERO

system is of the older type and it is not desirable or economical to change the exciter field circuit to include such equipment as the wheatstone bridge.

In the tests described, load was dropped by tripping the high-voltage transformer circuit breaker, therefore the effect of line charging current was not included. The effect of charging current is to give a higher value of voltage, the amount varying with the length and voltage of the line and the number of generators and transformers connected after load is lost.

ACKNOWLEDGMENTS

The author desires to express appreciation for the assistance rendered by the New York Power and Light Corporation in granting permission to make the tests, and to members of the Engineering Department of the General Electric Company for suggestions and valuable assistance in working up the data.

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Appendix

A Method of Calculating Alternator Over-Voltage Following Sudden Loss of Load

By J. W. Butler*

In this appendix equations are derived for calculating alternator overvoltage following sudden loss of load. The analysis is made for the bridge-type rheostat, but in general the same method can be used for other types of control.

Assumptions

Assumptions used in this article will be summarized below.

(*a*) *Pilot Exciter*

1. Time constant of shunt field so small as compared to the equivalent time constant of the speed-time curve that the shunt field current follows the speed exactly.

2. Load saturation curve coincides with the no load saturation over the operating range. This is approximately true for pilot exciters that are flat compounded and liberally designed.

(*b*) *Main Exciter*

1. Shunt-wound exciters will be considered as they are used in common practise at the present time.

2. Inductance of field circuit remains constant, but is corrected by a factor, depending on the type of field structure.

3. Open circuit instead of load saturation curve is used.

Assumptions 2 and 3 compensate in a measure for the effect of the voltage reduction following a higher curve than the saturation curve, due to eddy currents, when the field current decreases rapidly.

Pilot Exciter Armature Volts

With the above assumptions, the curve of pilot exciter armature volts may be readily obtained as follows:

From the saturation curve of the pilot exciter at normal speed, saturation curves for 110, 120, etc., per cent speed may be drawn. Then drawing in the field circuit resistance line, the voltage for any speed is read at the intersection of the resistance line and the saturation curve for that particular speed. From the values of voltage for different speeds obtained and the hydraulic turbine speed-time curve, a volt-time curve is obtained.

An empirical expression for this curve in operational form using one exponential is

$$e_1 = a + \frac{b-a}{T_1\,p+1} \tag{1}$$

Where a and b are the initial and final values respectively, and

$$T_1 = \frac{t_o}{\log_\epsilon \dfrac{b-a}{b-e_o}}$$

$$p = \frac{d}{d\,t}$$

e_o and t_o are the coordinates of a particular point on the curve. It is preferable to take a point in the region where the greatest accuracy is desired.

Main Exciter Field Current

The excitation circuit, employing the bridge-type rheostat, is shown in Fig. 13.

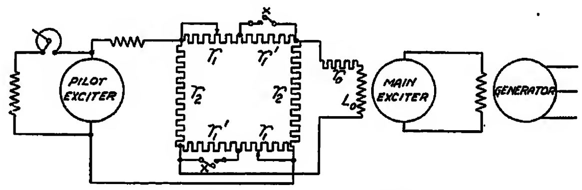

Fig. 13—Diagram of Excitation System Using Wheatstone Bridge Rheostat

The voltage e_1 operates upon the bridge circuit in which r_o and L_o is the shunt field resistance and inductance respectively, and r_1, r_1', and r_2 are the rheostat resistances. Upon indication of overvoltage, the regulator opens x, inserting r_1' in the circuit. The value of r_1' usually is sufficient to reverse the excitation.

Consider the case when the regulator fails to operate. The current through the main exciter field will be

$$i_o = \frac{a\,(r_2 - r_1)}{2\,r_1\,r_2 + r_o\,(r_2 + r_1)}$$

$$+ \frac{r_2 - r_1}{2\,r_1\,r_2 + (r_o + p\,L_o)(r_2 + r_1)}\;\frac{b-a}{T_1\;p\;+\;1}\,1 \tag{2}$$

The solution of which is—

$$i_o = \frac{a}{m} + \frac{b-a}{n\,T_1}\,(A_o + A_1\,\epsilon^{-a_1 t} + A_2\,\epsilon^{-a_2 t}) \tag{3}$$

$$m = \frac{2\,r_1\,r_2 + r_o\,(r_2 + r_1)}{r_2 - r_1}$$

$$n = \frac{L_o\,(r_2 + r_1)}{r_2 - r_1}$$

*General Electric Co., Schenectady, N. Y.

$$A_o = \frac{1}{a_1 a_2} \qquad a_1 = \frac{m}{n}$$

$$A_1 = \frac{1}{-a_1(a_2 - a_1)} \qquad a_2 = \frac{1}{T_1}$$

$$A_2 = \frac{1}{-a_2(a_1 - a_2)}$$

The high-speed relays x are opened by the voltage regulator in approximately three cycles after the indication of 5 per cent overvoltage which occurs the instant load is lost. Due to this quick operation and the time constants of the circuits involved, it can be assumed with very little error that the loss of load and opening of the relays x occur simultaneously.

Hence, the equation for the current after the regulator acts can be written thus

$$i_o = \frac{a(r_2 - r_1)}{2r_1r_2 + r_o(r_2 + r_1)} - 2\left[\frac{a(r_2 + r_o)}{2r_2r_1 + r_o(r_2 + r_1)}\right.$$

$$\left.\text{times}\ \frac{r_2 r_1}{2r_2(r_1 + r_1') + (r_o + pL_o)(r_2 + r_1 + r_1')}\right]1$$

$$+\frac{r_2 - r_1 - r_1'}{2r_2(r_1 + r_1') + (r_o + pL_o)(r_2 + r_1 + r_1')}\,\frac{(b - a)}{T_1 p + 1}1 \tag{4}$$

The solution being

$$i_o = Y_1 + Y_2\,\epsilon^{-a_2 t} + Y_3\,\epsilon^{-a_3 t} \tag{5}$$

where

$$Y_1 = \frac{b(r_2 - r_1 - r_1')}{2r_2(r_1 + r_1') + r_o(r_2 + r_1 + r_1')}$$

$$Y_2 = \frac{(r_2 - r_1 - r_1')(b - a)}{L_o(r_2 + r_1 + r_1')(a_2 - a_3)}$$

$$Y_3 = \frac{(r_2 - r_1 - r_1')(b - a)}{[2r_2(r_1 + r_1') + r_o(r_2 + r_1 + r_1')][(T_1 a_3 - 1)]}$$

$$+\frac{2a(r_2 + r_o)r_2r_1'}{[2r_2r_1 + r_o(r_2 + r_1)][2r_2(r_1 + r_1') + r_o(r_2 + r_1 + r_1')]}$$

$$a_3 = \frac{2r_2(r_1 + r_1')}{L_o(r_2 + r_1 + r_1')} + \frac{r_o}{L_o}$$

$$a_2 = \frac{1}{T_1}$$

Thus, equation (5) gives an equation of main exciter field current considering regulator action on the bridge rheostat and overspeeding of the pilot exciter.

This current flowing through the main exciter shunt field produces main exciter armature volts and current which will not be considered.

Main Exciter Armature Volts and Current

By plotting equation (5), the curve of main exciter armature volts can be determined considering the increase in speed as follows:

For any particular value of i_o flowing at time t, the voltage is read from the saturation curve. From the speed-time curve of the unit, the speed of the set can be read for the particular time t chosen and the voltage increased in direct ratio. The voltage function thus obtained operates upon the generator field.

The operational equation of such a curve, as shown for (1) is,

$$E = E_o + \frac{E_1}{T_2 p + 1}1. \tag{6}$$

The problem now is to find an equation of generator field current as a function of time. Having this, terminal voltage can be read directly from the saturation curve for any value of field current and corrected for the increased speed at the particular time chosen.

There are two factors affecting the generator field current. Upon sudden loss of load the field current drops immediately to a value necessary to produce flux back of transient reactance. It then builds up to a value that existed before loss of load according to the open-circuit time constant of the generator field circuit providing constant collector ring volts is maintained. But in this case under consideration, due to the increased speed of exciters and regulator action, the collector-ring voltage varies according to equation (6).

With the voltage expressed by equation (6) applied to the collector rings and considering the drop of current at $t = 0$, the following type of equation for generator field current will result:

$$I = I_o - I_o'\,\frac{p}{T_{do}'p + 1}1 + \frac{E_1}{r}\,\frac{1}{(T_2 p + 1)(T_{do}'p + 1)}1 \tag{7}$$

The solution being

$$I = I_o - I_o'\,\epsilon^{-c_1 t} + I_1(C_o + C_1\,\epsilon^{-c_1 t} + C_2\,\epsilon^{-c_2 t}) \tag{8}$$

Where I_o = field current before loss of load

$$I_1 = \frac{E_1}{r\,T_2\,T_{do}'}$$

T_{do}' = open circuit time constant of generator.
r = resistance of field circuit.
I_o' = the decrease in field current the instant load is lost.

$$C_o = \frac{1}{c_1 c_2} \qquad C_2 = \frac{1}{-c_2(c_1 - c_2)}$$

$$C_1 = \frac{1}{-c_1(c_2 - c_1)} \qquad c_1 = \frac{1}{T_{do}'}$$

$$c_2 = \frac{1}{T_2}$$

Plotting (8), the curve of generator terminal voltage can be determined by using the generator saturation curve and speed-time curve as was explained for main exciter armature volts.

Using this method of calculation, curve A' of Fig. 6 shows the calculated voltage of the 47,000-kva. generator under the test conditions of dropping load. This curve agrees very closely with the test voltage curve A, considering calculated machine constants were used and that there were 2 or 3 cycles of single-phase operation in dropping load.

Discussion

E. J. Burnham: In regard to the question of quick response excitation schemes now in use giving overvoltage protection such as described in the paper: Quick response excitation as ordinarily provided will not necessarily prevent the voltage of a waterwheel-driven generator from rising to an undesirable value upon dropping load. In the past many quick response excitation systems have been designed with reference to voltage build-up to take care of short-circuit conditions. Such systems, especially if series rheostats are used in the main exciter field, may permit the a-c. voltage to rise to a rather high value in case load is dropped. For example the 47,000-kva. waterwheel generator described in this paper will have the same quickness of response as far as build-up of excitation is concerned whether the series rheostat or wheatstone bridge rheostat is used, and in either case may be said to have a quick response excitation system. However, when dropping full load with the wheatstone bridge rheostat in service the a-c. voltage rises to 125 per cent of normal (Fig. 6) and when using a series rheostat under similar conditions, the a-c. voltage rises to a value approximately 145 per cent of normal (calculated).

As to the effect of adequate voltage control on lightning arrester design, the over-dynamic voltage permitted on a transmission system has a direct bearing on the efficiency and cost of the lightning arrester. The use of suitable overvoltage protective equipment prevents the high overvoltage resulting from dropping load on waterwheel generators and permits the use of standard lightning arresters. Unless the overvoltage is controlled, special arresters with increased safety factor are required to prevent possible arrester failure. The protective efficiency of the special arrester will be less than the standard and the increased cost may be comparable to the cost of the overvoltage protective equipment.

Interconnection of the 25- and 60-Cycle System of the Union Electric Light and Power Company

BY L. V. NELSON*
Associate, A. I. E. E.

and

E. E. HOUGH*
Associate, A. I. E. E.

History and Development

THE Mississippi River Power Company's hydro plant at Keokuk, Iowa, was developed in the years 1912-1913 as a 25-cycle run-of-river plant with an installed capacity of 135,000 kilowatts in 15 generating units. This plant was projected on the basis of a power contract with St. Louis utilities for 60,000 prime horsepower (45,000 kw.). The smaller city loads at Keokuk, Fort Madison and Burlington, Iowa, were also supplied from the plant. During 1930 the prime load demand reached 110,000 kilowatts with sufficient excess sales to load the plant to capacity over the daily peak.

As a run-of-river plant the capacity of Keokuk fluctuates over the seasons, being divided essentially into three periods:

1. A low-water winter period in which the capacity is reduced to 115,000 kilowatts.
2. A low-water navigation period in which the capacity is reduced to 83,000 kilowatts.
3. A high-water period in which the capacity of the plant is limited to 70,000 kilowatts.

The average duration of these limitations on the plant is 85 days, 102 days, and 150 days per year, respectively. With the average combined limitation for one reason or other of 252 days per year in which the capacity of the plant is less than 100,000 kilowatts, the relay requirements to the water power plant became an important factor. With only 40,000 kilowatts of steam reserve available at St. Louis to augment these periods of deficiency, and with an average rate of growth of 4,000 kilowatts a year on the 25-cycle system, additional relay capacity was needed if the 25-cycle load continued to grow at this rate. Further growth of 25-cycle load in St. Louis has been restricted for several years.

Consideration was given to a number of means of supplying this additional capacity:

1. Additional units at Keokuk. The original construction of the Keokuk Plant provided space for 15 additional units without reconstruction of coffer dams.
2. Installation of a steam plant at Keokuk.
3. Installation of additional 25-cycle steam reserve at St. Louis.
4. Installation of frequency converter at St. Louis.

Coincident with this same problem there arose the requirement for additional 60-cycle generation capacity to supply the rapidly growing metropolitan load at St. Louis. Simultaneous studies revealed the advisability of the development of the Osage Hydro Plant, located on the Osage River about 130 miles southwest of St. Louis, together with the interconnection of this plant with the St. Louis load through the Page Avenue Substation, which is also the terminus of the Keokuk-St. Louis Transmission Lines. The system map is shown in Fig. 1.

The 60-cycle load of 200,000 kilowatts demand growing at the rate of approximately 15 per cent a year required a yearly increase in 60-cycle generating equipment in excess of 30,000 kilowatts; whereas the annual growth in the 25-cycle system of 4,000 kilowatts average indicated that the reserve 60-cycle generating capacity required solely by the 60-cycle system could be reasonably utilized as 25-cycle reserve without additional prime mover investment for the 25-cycle system, providing suitable interconnection were arranged.

Studies of the 25-cycle system load curve as related to the limited schedule of Keokuk Plant capacity showed the loss of approximately 60,000,000 kw-hr. annually with available excess capacity up to 40,000 kilowatts. This was due to the inability of the 25-cycle load to absorb this energy when and if available, particularly during night periods.

The installation of the Osage Plant with its interconnecting transmission lines indicated the requirement at the St. Louis end of approximately 50,000 kva. in synchronous condenser capacity.

General Specification of Frequency Converter

Consideration of all of these facts from a coordinated point of view gave evidence of the desirability of interconnection between the 25- and 60-cycle systems with a suitable type of frequency changer. The frequency changer should have the following characteristics:

1. It should be reversible in order to provide:
   (a) 25-cycle power to the 25-cycle system to augment the combined water power and steam generation in times of water power deficiency. Comparison of the rates of growth of the 25- and 60-cycle systems indicated that the interconnection through the frequency changers would provide 25-cycle prime reserve without additional investment in 60-cycle generating equipment.
   (b) Access to the 60-cycle system for additional utilization of 60,000,000 kw-hr. annually from the 25-cycle system.
2. The machine should be of such type as would provide interconnection between a fixed capacity 25-cycle generating system of 175,000 kilowatts and an

*Both of the Union Elec. Light & Pr. Co., St. Louis, Mo.

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increasing 60-cycle system capacity with a present rating in excess of 450,000 kilowatts.

3. The 60-cycle end of the machine should combine approximately 50,000 kva. of synchronous condenser capacity for use in bringing Osage power into the St. Louis district.

4. Either end of the machine should be constructed to run separately in the event that the diversity between the water sheds of the Keokuk Plant and Osage Plant required such operation. This might also be required in the interest of economy in operation.

5. Two machines of one-half capacity each would be preferable to one since failure of one machine would still permit adequate operation under most cases.

namely, from Keokuk to St. Louis, with voltage drop along the transmission line compensated for by graded voltage ratings of the transformers to be connected at either end. As a result Keokuk transmitted at 112,000 volts and St. Louis received at 95,000 volts. No provision was made for a change of voltage under varying loads. This problem was imminently in need of adjustment and a study of the age of the transformers at Page Avenue, including efficiency, life, and voltage, indicated that with modern design and efficiency to be expected, a new bank of transformers was fully justified. Accordingly the old group of twelve 5,000-kva., single-phase, 95/13.8-kv. indoor type transformers were removed from service and replaced with six 12,500-kva.,

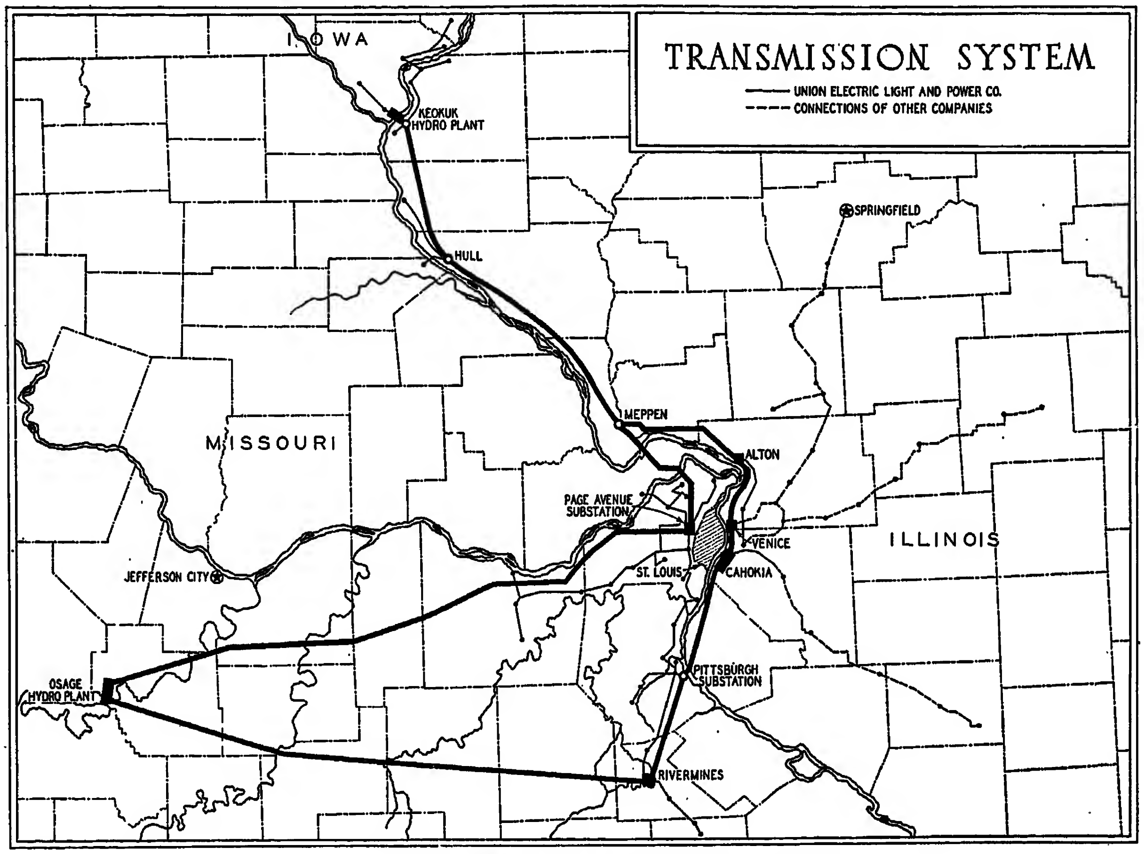

Fig. 1—System Map, Interconnected Systems

It was obvious that the combined advantages of the frequency changer made it superior to other possibilities of supplying 25-cycle reserve.

A study of growth of the 25-cycle load at Keokuk in preference to St. Louis shows that as time goes on the amount of energy generated at Keokuk and transmitted to St. Louis will decrease. Conversely, the amount of energy generated at St. Louis and transmitted toward Keokuk at 25 cycles will increase provided the plant capacity at Keokuk remains fixed. The latter amount is now in the order of a few per cent of the former.

Systems Interconnection

Early development of the Keokuk-St. Louis 25-cycle system anticipated one direction transmission of power,

single-phase, 110/13.8-kv. outdoor type transformers equipped with load ratio control. These new transformers provided facilities for full control of voltage in transmission of power in either direction without undue fluctuation of bus voltage at Keokuk or Page Avenue. The indoor type of transformers originally installed included an extensive and, in the light of modern practise, wasteful use of building space for 95-kv. bus layout. The removal of this indoor bus to a compact outdoor arrangement released sufficient space to provide for a new 13,800-volt, 60-cycle bus required for switching the incoming lines from Osage, and materially simplified the 25-cycle layout.

This coordination of 25- and 60-cycle systems at Page Avenue Substation interconnected to the major

source of supply, namely, Venice and Cahokia plants by means of two 66-kv. underground cable circuits providing an effective tie capacity of 100,000 kva. The one line system diagram is shown in Fig. 2.

Selection of Type of Set

The size of frequency converters required was determined by a study of the load requirements. Two sets of 20,000 kw. rating were chosen as combining most suitably the load transmittal requirements, spare capacity, and synchronous condenser requirements.

The type of set to be used was the subject of considerable investigation. It was found that there were five types of machines available, namely:

1. The synchronous-converter frequency converter.
2. The synchronous-synchronous converter.
3. The synchronous-induction converter.
4. The fixed-ratio synchronous-induction converter.
5. The variable-ratio synchronous-induction converter.

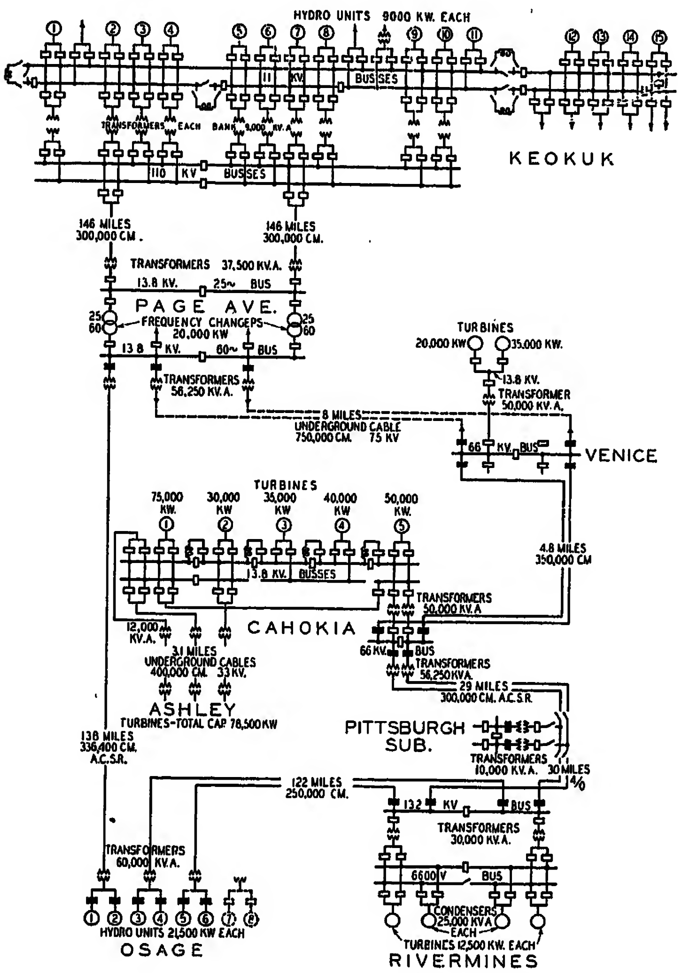

Fig. 2—Interconnected—System Diagram

Each type of machine was analyzed in detail with its adaptability to the particular situation in mind.

Synchronous Converter Set. The synchronous-converter frequency converter consists of two synchronous converters on independent shafts, one operating from each of the systems to be interconnected. All power transferred is received at one frequency, converted to direct current and reconverted to alternating current of the other frequency. The fact that this machine has never been built in large sizes definitely precluded its use in this case.

Synchronous-Synchronous Set. The synchronous-synchronous converter consists of two synchronous machines on a common shaft, one operating on each system. This machine is the one most commonly used. The frequency ratio is fixed and, therefore, the set constitutes a rigid frequency tie between systems within the limits of pull-out torque of the individual machines. The set is completely reversible, the load transmittal being determined solely by prime mover governing and cannot be controlled at the set. Power-factor control of both ends is available through a wider range than on any other type of set. The efficiency is high, preliminary estimates indicating that 95 per cent might be expected on a 20,000-kw. unit. This set is essentially simple in construction and operation and requires few auxiliary machines. The paralleling of machines requires considerable preciseness of synchronizing however. For example, when starting from the 60-cycle end there is only one chance in twenty-four of the machine "coming up" right. Load division between sets is readily accomplished by stator shifting. Machines of this type in the rating proposed had been built so no untried designs would be necessary.

Records indicated that the reliability of this type of set was good provided the machines were of sufficient capacity to withstand shocks incidental to system disturbances. The chief difficulty in applying this machine is the proper determination of the size of unit required. An examination of available data indicated that a capacity equal to from 10 to 25 per cent or more of the capacity of the smaller system would be required. This application would require a set of from 18,000 to 40,000 kw. capacity. Conservatively, it appeared that units of 30,000 to 40,000 kw. each would be required and since load transmittal requirements did not justify units of this size it seemed undesirable to use this type of converter.

Synchronous-Induction Set. The synchronous-induction converter consists of a synchronous machine direct-connected to an induction machine of either the wound rotor or squirrel cage type. The frequency ratio of this set varies according to the load on the set and is not controllable at the set. The set is reversible if sufficient synchronous capacity is available to supply the exciting kva. of the induction machine. There is considerable change in frequency ratio with change in direction of power flow. Load control is determined by prime mover governing. The set is relatively stable, the stability being determined chiefly by the pull-out torque of the synchronous machine. Power-factor control is avail-

able on the synchronous end of the set but not on the induction end. The efficiency is relatively low. The set is simple in construction and operation and the reliability is good.

Fixed-Ratio Induction Set. The fixed-ratio synchronous induction converter consists of a synchronous machine and a wound rotor induction machine with the rotor of the induction machine and the stator of the synchronous unit connected to the lower frequency system and the stator of the induction machine connected to the system of higher frequency. This converter is sometimes called the "general transformer" since it can be arranged to transform phase, frequency, and voltage. A peculiar characteristic of this set is that it constitutes a voltage tie between systems of different frequencies in a manner analogous to a transformer on a single-frequency system. In several cases this set has been used to obtain certain advantages which this characteristic gives under particular circumstances. In the case at hand this feature was undesirable.

The frequency ratio is fixed by the design and is rigid. The set is reversible and the load control is obtained by prime mover governing. Stability is good and limited power factor control is available by a combination of transformer tap changing and synchronous machine field control. The efficiency is relatively high and operation is relatively simple although there is only one chance in ten of correct polarity and phase on the second unit. This type of machine has been reliable in service and has been built in large sizes. In the event of a short circuit on the lower frequency system the set overspeeds.

With this type of machine, also, the selection of the proper size of unit is difficult, the determination requiring a consideration of the same factors that govern in the selection of synchronous-synchronous machines.

Variable-Ratio Induction Set. The variable-ratio synchronous-induction converter consists of a synchronous machine direct-connected to a wound rotor induction machine provided with suitable regulating machines, the number and type varying with the particular manufacturer. The distinguishing feature of this set is that the frequency ratio is variable, that is, frequency of one system may vary relatively to that of the other. Voltage and load disturbances are reflected through the set in a lesser degree than with other types. The set is reversible and load control is accomplished at the set itself without dependence on prime mover governing within the design limits of the set. Stability is good, the load transmittal being determined by the pull-out torque of the synchronous machine, the relative speed changes of the two systems and the speed of operation of the regulating equipment. It is interesting to note that if the automatic regulating equipment is not working it requires a relative speed change of twice the slip of the induction machine to reverse the set from full load in one direction to full load in the other whereas with fixed-ratio types this reversal occurs with only a small phase angle change. Power-factor control through a wide range can be obtained on the synchronous machine and through a limited range as determined by economic design considerations on the induction machine. Efficiency is good although not as high as on synchronous-synchronous machines. The efficiency varies with variation in frequency ratio. The set is somewhat complex although its operation is simple.

The main advantage of this set lies in its stability and in the ease with which the sets may be started and the load controlled. Automatic control of load is readily obtained. The sets had been built in the size contemplated and component machines of larger sizes had been produced.

The relative merits of the various converters for the particular interconnection contemplated is summarized in Table I.

Based on this analysis it was decided to purchase two variable ratio synchronous-induction converter sets, each set to be capable of transmitting 20,000 kw. from the 25- to the 60-cycle system or vice versa with simultaneous and opposite variations in normal frequency of one-half cycle in each system. That is, each set was to be capable of transmitting full load from either system to the other throughout frequency variations from 24.5/60.5 to 25.5/59.5 cycles. This permits a rather wide variation in the frequency of one system if that of the other is fixed, the range being affected because of the natural slip of the induction machine, by the direction of load transmittal.

The sets as purchased are General Electric Company machines with essential data as tabulated in Table II.

The machines are of the 6-bearing horizontal type with adequate provisions for movement of stators on both large machines to permit easy maintenance or repair. A split coupling is provided between the 25- and 60-cycle ends of the machines with the starting motor and d-c. exciters on the 60-cycle end to permit operation of the 60-cycle unit independently as a synchronous condenser if required. Each unit occupies an area of approximately 13 by 60 ft.

The ventilation requirements are 150,000 cubic ft. of air per minute per machine. All air into the room is filtered through continuous type filters. The machines are the semi-enclosed type, drawing air from the room and discharging into the basement. Air is forced out of the basement through large chimneys at the building ends which discharge just above the roof of the building. A view of the building housing the machines is shown in Fig. 3, one of the chimneys being visible at the right. The converters installed are shown in Fig. 4.

Operation

The frequency converters have, at this writing, been in service for some six months and have fully met every expectation although definite conclusive results of

operation cannot yet be evaluated. They operate over a part of the day as 60-cycle generators utilizing the excess 25-cycle water power from Keokuk and the balance of the time as 25-cycle generators supplying 25-cycle relay power. During the first six months' operating period covering initial tests and operation on the normal load cycle outlined above the average over-all efficiency has been approximately 90 per cent.

TABLE I—CHARACTERISTICS OF FREQUENCY CONVERTER SUITABLE FOR INTERCONNECTION OF 25- AND 60-CYCLE SYSTEMS OF UNION ELECTRIC LIGHT AND POWER COMPANY

Characteristic	Variable-ratio Synchronous-induction	Fixed-ratio Synchronous-induction	Synchronous-synchronous	Variable-ratio machine suitability for contemplated interconnection
Load control determined by	Regulating equipment at machine (can be held constant by automatic control)	Prime mover governing	Prime mover governing	Preferable
Load limit determined by	Regulating equipment, relative system speeds and synchronous machine stability	Synchronous machine stability	Synchronous machine stability	Preferable
Machine size determined by	Load transmittal requirements	System synchronizing requirements	System synchronizing requirements	More economical
Voltage tie	No	Yes	No	Preferable
Frequency tie	Flexible	Rigid	Rigid	Suitable
Power-factor correction	Limited to unity on induction end and by machine design on synchronous end	Limited to synchronous machine design and transformer tap range	Limited by synchronous machine design	Satisfactory—requirement for corrective capacity on 25-cycle system is limited
Set complexity	Several auxiliary machines	Considerable auxiliary apparatus	Simple	At a disadvantage
Starting first set	Simple	Difficult	Difficult	Preferable
Starting second set	Simple—same as the first one	Very difficult	Difficult	Preferable
Load balanced between sets	By regulating equipment	By stator shifting	By stator shifting	Preferable because load is always controlled in same manner
Cost	Highest	Intermediate	Lowest	At disadvantage
Expected efficiency	93 per cent	94 per cent	94.2 per cent	Satisfactory
Experience in building sets of required size	Yes	Yes	Yes	On a par with others
Reliability	Good	Good	Good	Equal of others
Short-circuit output of lower frequency machine	Low	High	Intermediate	Preferable in order to eliminate extensive switchgear changes

TABLE II—DATA ON 20,000-KW. FREQUENCY CONVERTERS UNION ELECTRIC LIGHT AND POWER COMPANY

	Synchronous machine	Induction machine	Starting motor	D-c. exciter	Pilot exciter	Regulating machine	A-c. exciter	Exciting transformer
Volts	13,800	13,800	13,800	225/250	240/250	285	35	13,800/37
Kilowatts	20,000	20,000	...	195	5	...	...	...
Kilovolt-ampere or horsepower	28,600 kva.	28,700 hp	1,200 hp	...	...	890 kva.	8 kva.	35 kva
Amperes	1,196	980	66	780	20	1,800	100	...
Power factor	70 per cent	1.0	...	...	...	...	...	...
Speed	300	300	320	300	300	300	300	...
Cycles	60	25	60	...	...	Slip	25/slip	25
Poles	24	10	22	8	4	18	10	...
Phases	3	3	3	...	...	3	6/3	3/6
Corrective kva. zero load	31,200	16,000	...	...	...	...	...	...
Corrective kva. full load	20,000	0	...	...	...	...	...	...

Power from the Bagnell Dam is not yet reaching the St. Louis District and consequently the machines have not been fully utilized for power-factor correction on the 60-cycle system.

It has been found that the inherent ability of the machines to change load gradually with system speed changes has been of marked benefit in stabilizing the systems. For example, with the set feeding the 25-cycle system a voltage dip may cause the loss of considerable 25-cycle load with consequent speeding up of that system. The set reverses and the frequency is held to a small departure from normal. The 60-cycle machines are equipped with high-speed excitation systems so that

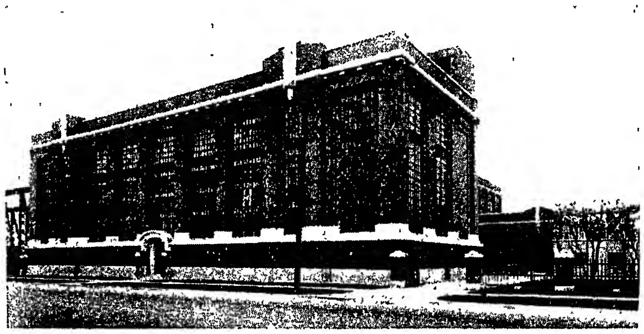

FIG. 3—PAGE AVENUE SUBSTATION BUILDING

the 60-cycle voltage is held within narrow limits. The corrective capacity in the 25-cycle induction units varies from zero at full load to 16,000 kva. at no load and exerts a remarkable stabilizing influence on the 25-cycle voltage.

When a short circuit occurs on the 25-cycle system, obviously the exciting voltage is reduced to a low value and consequently the decrement curve shows a very rapid drop after the first few cycles. This has the effect of holding the interrupting requirements on oil-circuit breakers to a low value.

The machines as installed cannot be operated unless a 25-cycle exciting source is available. Minor modifications would permit direct-current excitation to bring up a dead system. In several cases where the 25-cycle bus voltage has been dropped to a very low value by faults close into the bus the machines have resynchronized themselves inherently without any difficulty. In this connection it is of interest that the voltage of the induction unit is always at the same frequency as the exciting source but its value may vary through wide limits and it may be considerably out of phase with the system voltage. Consequently, the ability to resynchronize depends upon the action of the regulating

FIG. 4—TWO 20,000-KW. VARIABLE-RATIO FREQUENCY CONVERTERS AT PAGE AVENUE SUBSTATION

equipment and the changes in relative system speeds during the interval when the bus voltage is very low.

The tested machine efficiencies were considerably higher than anticipated in the original estimates, the actual values including all losses for various operating conditions being given in Table III.

TABLE III—EFFICIENCIES OF 20,000-KW. FREQUENCY CONVERTERS

Frequency ratio	Power factor		Load			
	Induction machine	Synchronous machine	1.0	0.75	0.50	0.25
25/60	1.0	1.0	94.98	94.49	93.94	90.08
25/60	1.0	0.70 overexcited	94.28	93.94	93.94	89.86
25.5/60	1.0	1.0	94.96	94.46	93.90	90.00
24.5/60	1.0	1.0	94.91	94.41	93.82	89.90
24.5/60.5	1.0	1.0	94.88	94.40	93.73	89.80
24.5/60.5	1.0	0.70 overexcited	94.18	93.82	93.38	89.53

NOTE: Above figures are overall including losses in exciters, regulating machines, and blowers, where required.

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1. *Use of Frequency Chargers for Interconnection of Power Systems.* H. R. Woodrow, A. I. E. E. TRANS., 1925. Describes Brooklyn Edison fixed-ratio synchronous induction machine.

2. "Variable Ratio Frequency—Changer Sets." C. W. Kincaid, *Elec. Jl.*, June 1928, p. 279. Describes various variable-ratio machines with particular reference to Westinghouse designs.

3. *Interconnection of Power and Railroad Traction Systems by Means of Frequency Changers.* Ludwig Encke, A. I. E. E. Trans., Vol. 47, Oct. 1928, p. 1056. Gives general theory and describes both Westinghouse and General Electric machines of variable-ratio type installed by New Haven Railroad.

4. *Application of Large Frequency Converters to Power Systems.* E. J. Burnham, A. I. E. E. Trans., Vol. 47, Oct. 1928, p. 1070. Describes various types of frequency converters with particular reference to variable-ratio sets.

5. *A 35,000-Kw. Induction Frequency Converter.* O. E. Shirley, A. I. E. E. Trans., 1924, p. 1011. Describes New York fixed-ratio machines giving operating characteristics and test data.

6. "Frequency Converter Tie between Large Power Systems." J. W. Dodge, *Gen. Elec. Rev.*, June 1923. Outlines types available and gives salient features of each.

7. "Parallel Operation and Synchronizing of Frequency Converters." O. E. Shirley, *Gen. Elec. Rev.*, Feb. 1920. Outlines operating problems in connection with synchronous-synchronous sets.

8. "35,000-Kw. Synchronous Frequency Changer Set." M. W. Smith, *Elec. Jl.*, July 1924, p. 343.

9. *A 40,000-Kw. Variable-Ratio Frequency Converter Installation.* Bundy, Van Niekerk, and Rodgers, A. I. E. E. Trans., Vol. 49, p. 245.

10. *Automatic Control for Variable-Ratio Frequency Converters.* Shively and Whitlow. Presented at the South West District Meeting, Kansas City, Mo., Oct. 22-24, 1931.

Discussion

R. H. Park: As brought out by Messrs. Nelson and Hough, there are three principal types of synchronous converters available in large sizes. These are the synchronous-synchronous type, the fixed ratio synchronous-induction type, and the variable-ratio synchronous-induction type.

The first type is the cheapest and most efficient and will frequently be found satisfactory from an operating standpoint. It is believed, however, that many cases arise in which the use of the second or third type is justified in view of the particular operating advantages which they may afford.

For instance, in the case of those metropolitan systems which do not employ generator voltage regulators, there may be a considerable advantage in the use of the fixed ratio synchronous-induction type. Thus when a voltage tie is provided, as is the case with this type of unit, there is less danger of voltage instability in case of the loss of a large unit in either system, since a relatively large amount of wattless kva. can be transferred between systems with only a comparatively slight drop in voltage in the system which is in difficulty.

On the other hand, in many cases, and particularly when large systems, in which relatively large amounts of power are transmitted over overhead wires, are to be tied together, there is a likelihood that the power transfer through the frequency converters connecting the two systems will become excessive during disturbances in either system, if the frequency converter is of the type which establishes a rigid frequency tie. As a consequence, the frequency converter unit or units may pull out of step, and relay out of service. In such cases, the use of a variable-ratio synchronous-induction type frequency converter may be of particular advantage, as, with this type, disturbances may occur in either system which are sufficiently severe to cause a considerable change in frequency, without the overloading or pulling out of step of the frequency converter unit.

While the choice of type of unit will depend greatly on the method of operation and the frequency of occurrence of system disturbances, it would appear that for the interconnection which forms the subject of the paper under discussion, the use of the variable-ratio synchronous-induction type of frequency converter possesses particular advantages.

E. L. Hough: The variable-ratio frequency convertor is not a panacea for all interconnections between systems of different frequencies and we have endeavored to point out in the paper that the analysis was based on the particular system under discussion and not on the problem in general. A certain feature of a certain type of set may meet a definite operating problem on a particular system and this one feature may outweigh other considerations. An example of this is the use of large fixed ratio synchronous-induction machines on large metropolitan systems where voltage regulators are not used and a voltage tie between systems is highly desirable. On the other hand, in our particular system it was felt that a voltage tie was not only unnecessary but undesirable as well because of the relative importance of the two systems.

The size of set to be used is determined by different conditions in different situations. As pointed out in the paper, on the St. Louis system the determining factor was load transmittal rather than synchronizing requirements together with a high degree of reliability. Quite obviously a good solution of this engineering problem, as with others of a similar nature, requires the provision of the required facilities at a minimum cost and if a synchronous-synchronous machine of lower cost than a variable-ratio machine can perform satisfactorily, it should be chosen irrespective of whether or not it is of the same size as the variable-ratio machine. In searching for a solution to the Page Avenue interconnection we were unable to obtain guarantees from the manufacturers to the effect that a synchronous-synchronous machine of *equivalent cost* would hold the systems together. A search of the technical press revealed a considerable array of opinions on the size machine required, but no supporting data for the opinions. For example, Mr. Kincaid in the *Electric Journal*, June 1928, recommends machines equivalent to 15 to 20 per cent of the smaller system capacity where the one system is chiefly supplied from hydroelectric plants. Machines of this size would be more expensive than the type chosen and their losses would be higher because they would always operate at partial load.

The ability of the Scherbius type of machine to ride through system disturbance is superior. Due to the natural slip characteristic of the induction machine it requires an actual change of relative system frequencies to cause a change in load transmittal even with the load control equipment blocked or unable to operate with sufficient speed. However, we expect to obtain considerable benefit from the load control equipment because it can run from limit to limit in about 10 seconds and system disturbances require considerable time to materially affect system frequencies. As an example, assuming the induction machine has a natural slip of 2 per cent at full load, in the event the set were loaded to 20,000 kw. capacity, a drop in speed of 1 per cent on the system receiving power from the set would add only 10,000 kw. to the set load, even though the load control were ineffective. With a rigid frequency tie a drop of only a few degrees in phase angle would give a similar result.

While it is true that the stability limit of the Scherbius set is determined by the synchronous machine if voltage is maintained on the induction end it is apparent that the inherent WR^2 effects and reserve capacity of the whole system are brought into play to smooth out the disturbance and allow time for faults to clear without relaying the machine out of service.

As pointed out, the rapid short-circuit decrement reduces the strain on switchgear but may introduce other undesirable consequences. This particular feature must be carefully watched in determining relay settings and may, in some cases, require high-speed relays to take advantage of the initial short-circuit current of the machine which compares quite favorably with an equivalent synchronous machine.

From a reliability standpoint we expect little more difficulty from the a-c. commutating machines than we would from d-c. exciters. Most of the difficulties experienced with these ma-

chines in the past have been on those machines operating at a relatively much higher frequency than is the case in this installation. The regulating machine is of the generator type and lends itself readily to compensation. With maximum frequency spread the frequency on the a-c. commutating machine is 0.7 cycle and at normal frequency the commutating machine operates as a continuous current generator.

We expect better performance of the main units of these sets than we would have expected on a rigid frequency tie machine because shocks are cushioned. On a 5,000-kw. machine previously installed a great amount of difficulty was experienced with the amortisseur windings overheating and with winding failures. Similar difficulties have been reported by other operating companies (Trans. A. I. E. E., 1923, Vol. 42, p. 1078).

Up to the present time no commutating difficulties have been experienced and although a number of serious disturbances has occurred on the interconnected systems no difficulties whatever have been experienced with the machines that are not directly attributable to the inexperience of the operators or to incorrect adjustments. In one case, a short circuit on the 25-cycle bus to which the Scherbius unit is connected was cleared properly and the machine resumed its load automatically, although the bus voltage reached a very low value. In another case, during a sleet storm, the lines to the Keokuk Plant developed "dancing conductors" and one line was removed from service. The second line continued to swing together and clear itself for some time. On each occurrence of low voltage the machine output went to a very low value and recovered as soon as voltage came up and the operator being unfamiliar with such operation (a synchronous machine performing in an exactly opposite manner) assumed the machine to be at fault and removed it from service. From all available indications the clearing of the faulty high-tension line would have left the machine carrying its normal load with excitation from the steam system. The transformer method of excitation lends itself peculiarly to satisfactory operation under conditions such as these.

Automatic Control for Variable-Ratio Frequency Converters

BY E. K. SHIVELY* and GEO. S. WHITLOW†
Associate, A. I. E. E. Associate, A. I. E. E.

Synopsis.—An automatic switching equipment for the control of two 20,000-kw. frequency changer sets using the Scherbius method of load and power factor control has been in successful operation at the Page Avenue station of the Union Electric Light and Power Company of St. Louis, for almost a year. This equipment contains several new features in the automatic control of machines of this type. Besides being the first completely automatic switching equipment applied to machines of this type, it is unique in that it controls the largest rotating machines to which automatic switchgear has ever been applied.

The Page Avenue station is one of the most important links in this Company's system of interconnecting plants. It is the point through which the two 25-cycle generating stations, Ashley Street and Keokuk, are tied. It will also be used as one of the ties for the recently completed Bagnell development, on the Osage River, to the 60-cycle generating system of the metropolitan area. These variable-ratio frequency converters are being used for the transfer of power between the 25-cycle and 60-cycle systems.

* * * * *

General Description

THE sets consist of seven units on one shaft. These units are, in the order of their physical location, a 250-volt, 5-kw. subexciter; a 250-volt, 192-kw. main exciter; a 13,800-volt, 1,200-hp. (intermittent) 60-cycle starting motor; a 13,800-volt, 28,600-kva. 60-cycle synchronous machine; a 13,800-volt, 28,700-hp. 25-cycle wound rotor induction machine; a 285-volt, 890-kva. regulating machine and an 8-kva. 25-cycle a-c. exciter. There is a removable coupling between the first four and last three units. The speed of the sets is 300 r. p. m. at 60 cycles.

The sets will normally be operated as variable-ratio frequency converters to transfer load in either direction as dictated by system conditions. Both the synchronous and induction machines will supply a limited amount of corrective kva. to the respective systems. The amount of this kva. depends upon the loading of the sets, and can be readily determined for any condition of load by referring to the curves of Fig. 2. If it is so desired, the starting motors, the exciters associated with the 60-cycle units, and the 60-cycle units may be uncoupled from the 25-cycle ends and operated alone as condenser units.

The switching equipment is designed so that the starting, synchronizing, voltage control, load limiting features and protective devices are completely automatic. The control rheostats and switchboards on which the protective devices and automatic relays are mounted, are located on the main machine floor. On the operators' board in the balcony the machine meters and control switches are located. The operator may assume complete control of the equipment at any time by merely turning a control switch from the automatic to the manual position. If the set is in operation, this transfer can be made in either direction without disturbing the operation in any way. Figs. 3, 4, 5 and 6 show general views of the control rheostats and switchboards for one unit.

Synchronous Unit

Starting and Synchronizing. The starting is accomplished with no perceptible disturbance to the system by a wound-rotor induction-type starting motor. This motor has two less poles than the main 60-cycle machine so that when all of the starting resistance is short-circuited, the starting unit will drive the set at a speed slightly above synchronism.

When the initial starting indication is given by means of a control switch, the equipment checks that none of the protective devices has operated, that the starting and synchronizing breakers are in the open position and that normal three-phase voltage is available. If all of these conditions are satisfied, the main 60-cycle oil circuit breaker is permitted to close, which connects the machine bus to the station bus. This operation causes the bearing oil pump motors to start, and after a definite time, sufficient for the oil pressure to build up and lift the machine rotor, the starting motor is energized. Soon after the machine has begun to rotate, the oil pumps are shut down. After the initial starting current has decreased to a predetermined amount, showing that the machine is rotating, successive steps of secondary resistance are short-circuited at definite time intervals until sufficient resistance has been shunted to allow the set to run at slightly below synchronous speed.

During this part of the starting period the subexciter voltage is allowed to build up; this in turn energizes the field of the main exciter. When the machine has reached almost synchronous speed, the field of the synchronous unit is energized and the automatic voltage regulator assumes control of the machine voltage. Normal voltage is then apparent on both sides of the synchronizing breaker and the speed-matching and synchronizing equipment takes control and proceeds to synchronize the machine.

The last step of starting resistance that is shunted

*Union Elec. Light & Pwr. Co., St. Louis, Mo.

†Engg. Dept., General Elec. Co., St. Louis, Mo.

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before field is applied to the synchronous unit, is, as has been stated, sufficient to bring the set up to just below synchronous speed. As this speed is below synchronism the speed matching equipment will cause the last section of resistance to be short-circuited as soon as voltage has built up on the main unit. If the set exceeds synchronous speed and does not synchronize, the speed-matching equipment will insert this last section of resistance to decrease the speed.

The speed control equipment uses the relative vector rotation of the machine and bus voltages to determine whether the machine speed is to be raised or lowered. Fig. 7 shows the vector relationship of the voltages used in this equipment. The voltages *B*-1, *B*-2, *B*-3 are supplied from the station bus potential transformers. Voltage *M*-1, *M*-2 is obtained from *A-B* phase of the machine. Contactor coils are connected between the free ends of each of the bus voltages and the machine voltage. The diagram shows the vectors at a position where equal voltages are applied to the contactors, but neither has sufficient voltage to cause it to close its contacts. If the machine voltage rotates clockwise with respect to the bus voltage, indicating that the machine is running too slow, the voltage across 15 *R-C* will increase sufficiently to pick up this contactor, and cause resistance in the starting motor secondary to be shunted. If the vectors rotate in the opposite direction, relatively, 15 *L-C* will pick up and cause resistance to be inserted. It will be seen, because of interlocking, that only one of the contactors can be picked up simultaneously, and that one contactor does not drop out until the voltage across the other has decreased to an amount that is insufficient to pick it up.

When the frequency of the set has been matched sufficiently close to that of the system, the synchronizing relays initiate the closing of the synchronizing breaker when the two voltages are in the proper phase relation. The closing of this breaker is initiated a few degrees before the voltages reach the "in-phase" relationship provided the relative motion of the two vectors is not too fast, which would cause the actual synchronizing to take place after the "in-phase" position was reached, or too slow, which would cause just as severe a disturbance by allowing the synchronizing breaker contacts to make before the proper phase relationship is reached.

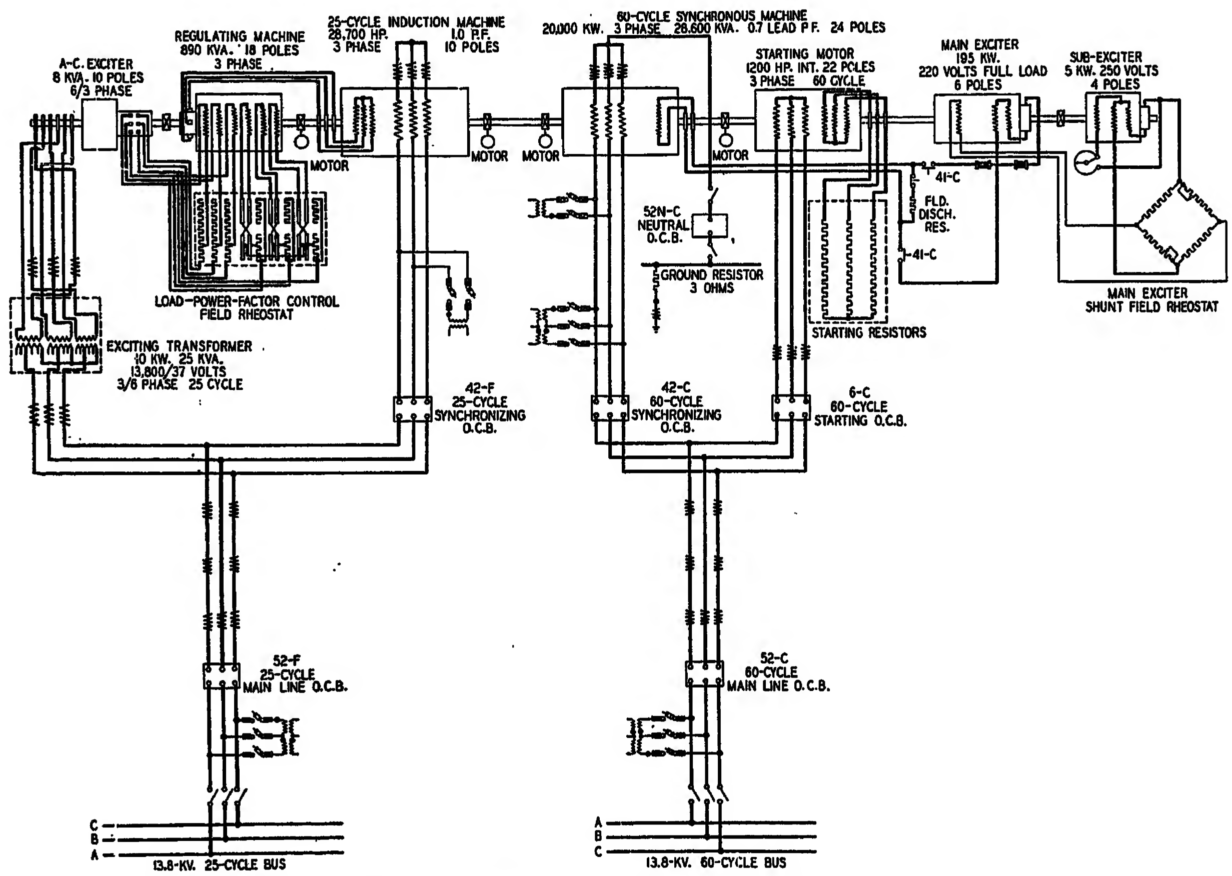

FIG. 1—DIAGRAM SHOWING MAIN CONNECTIONS FOR 20,000-KW. VARIABLE-RATIO FREQUENCY CONVERTER

Protection. The 60-cycle machine is protected against overload on the starting motor, incomplete start, winding failures, ground faults and undervoltage while starting, by relays that will trip the main oil circuit breaker. In case of a winding fault, incomplete start or overload on the starting motor, a lockout relay is actuated, which makes it necessary to inspect the equipment and reset this relay before further operation can take place. If a bearing overheats, an alarm is

sounded for the attendant who has control of the bearing cooling water. He will admit more cooling water to the bearing in distress. In case of an appreciable decrease in excitation, indicating that the machine is delivering an excessive amount of underexcited reactive

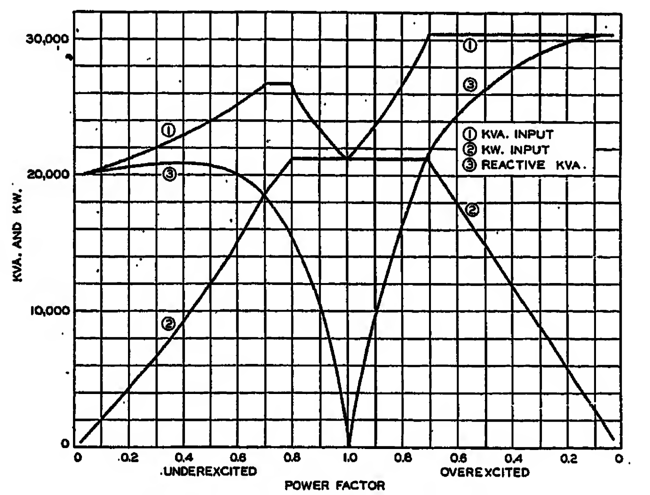

Fig. 2a—Maximum Kva. Curves for 60-Cycle Machine

kva., an alarm is sounded for the switchboard operator in the balcony. This operator, who has control of the load ratio control transformers, changes taps on these transformers to transfer some of this reactive kva. to other synchronous machines on the system.

Voltage Regulation. The generator voltage regulator

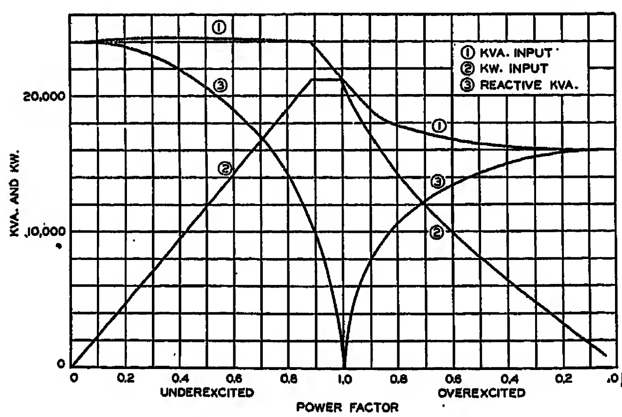

Fig. 2b—Maximum Kva. Curves for 25-Cycle Machine

used with this equipment is one that was developed primarily to eliminate the use of continuously operating vibrating contacts. The regulator performs two functions simultaneously. Upon changed conditions of load or power factor, the regulator immediately meets the changed conditions by rapidly varying the exciter voltage to meet the new excitation requirements. At the same time it operates the motor-driven exciter field rheostat until a corresponding constant exciter voltage is reached. The regulator then remains inoperative until another change requires a different value of excitation.

When operating as a synchronous condenser to correct the power factor of a system, it is sometimes necessary to produce a maximum of underexcited reactive kva. To do this the excitation of the exciter must be reduced to zero or even reversed slightly to overcome the residual, in order that the exciter voltage may be reduced to zero. The wheatstone bridge arrangement of connections of the exciter field rheostat and a separate

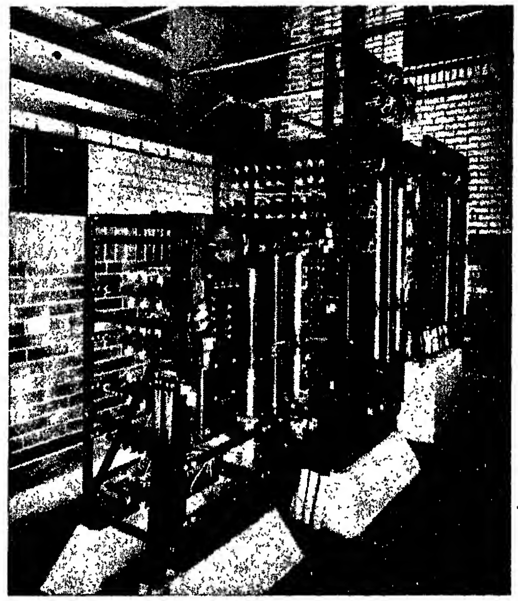

Fig. 3—Voltage and Power Factor Control Rheostats for One Frequency Converter Set

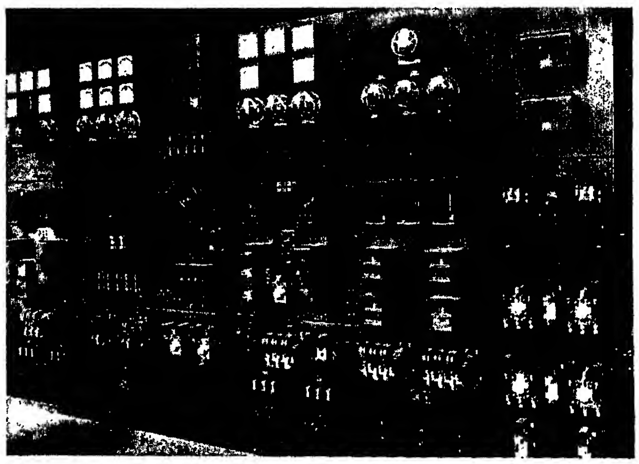

Fig. 4—East Section of Automatic Control Panels for No. 1 Frequency Changer Set

exciter are used for this purpose. The diagram of this arrangement is shown in Fig. 8. In this arrangement two arms of the bridge circuit are fixed and the other two variable. The variable arms have sufficient resistance to balance the bridge and reduce the exciter voltage to zero.

Induction Unit

Excitation System. Excitation is supplied to the armature of the a-c. exciter by a 25-kva. 13,800/37-volt,

three-phase/six-phase connected transformer. The high-voltage winding of this transformer is connected in Y to the 25-cycle 13,800-volt station bus through the 25-cycle main line oil circuit breaker. The low-voltage winding is connected six-phase diametrical

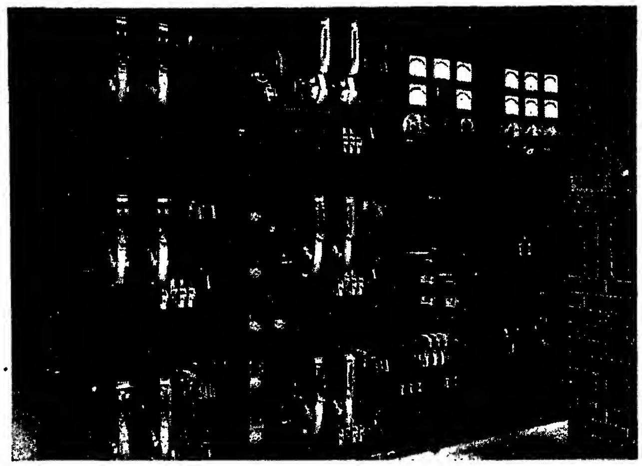

Fig. 5—West Section of Automatic Control Panels for No. 1 Frequency Changer Set

to the six slip rings of the a-c. exciter. The armature of this exciter is like that of a rotary converter, having both commutator and slip rings. The field punchings, however, which surround the armature are without slots or windings and serve simply to complete the

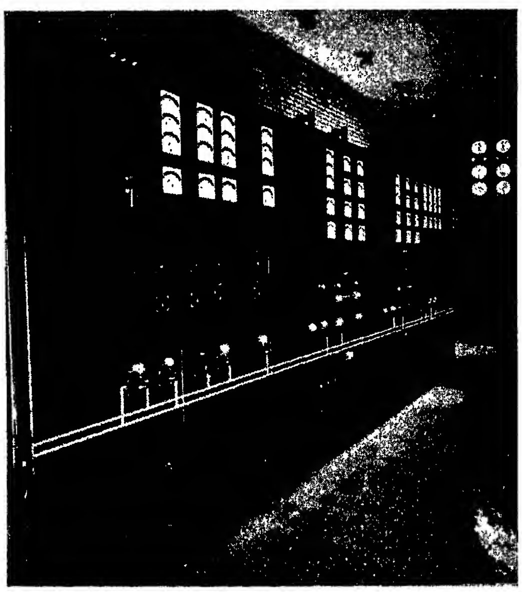

Fig. 6—Station Operator's Control Board on Balcony

magnetic circuit of the armature. The commutator brushes are carried on two brush yokes, the arms of which are spaced 120 elec. deg. apart around the commutator.

The brush yokes are shifted by a pilot motor. One yoke, referred to as the geared yoke, is connected to the pilot motor through reduction gearing while the other, referred to as the cam yoke, is shifted from the pinion gear shaft by means of a cam and roller. The two yokes travel at unequal speeds sometimes in the same direction, sometimes in the opposite direction, depending upon the position of the cam. The commutator brushes of the exciter are connected through the power factor control rheostat to the load control and power factor control fields of the Scherbius regulating machine. Fig. 10 shows schematically how these fields are connected. The voltage impressed on the power factor

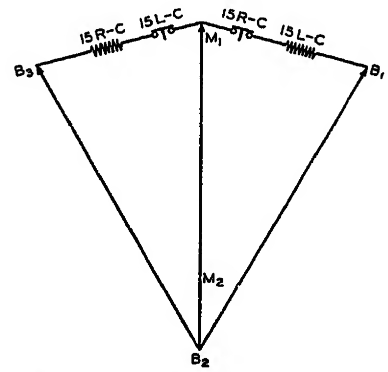

Fig. 7—Fundamental Diagram Showing Operation of the Speed Matching Relays

control field circuit is practically constant at all times. The voltage impressed on the load control field circuit, however, depends upon the amount of brush separation on the a-c. exciter, the greater the separation, the higher the voltage. When the brushes of both yokes rest upon

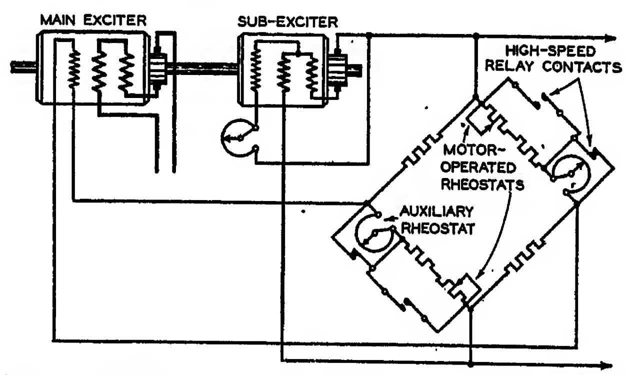

Fig. 8—Schematic Diagram of Excitation System of Synchronous Machine

the same commutator segment the voltage impressed on the load control field is zero. This is referred to as the neutral brush position.

The basic principle of the Scherbius regulating machine is the same as that of the neutralized d-c. machine with separate excitation. The armature and commutator are of the ordinary type of construction used in d-c. machines and voltage is generated by the rotation of the armature conductors through the field produced by the stator winding. The commutator brushes of the regulating machine are connected to the three rotor slip

rings of the 25-cycle induction unit. The excitation thus furnished to the rotor has a frequency which is equal to the difference between the bus frequency and the frequency which the 25-cycle unit would have as a synchronous machine at its driven speed. The difference between these two frequencies will be referred to as slip frequency. Thus if the frequencies of the two systems are exactly 25 and 60 cycles, or, if the frequency

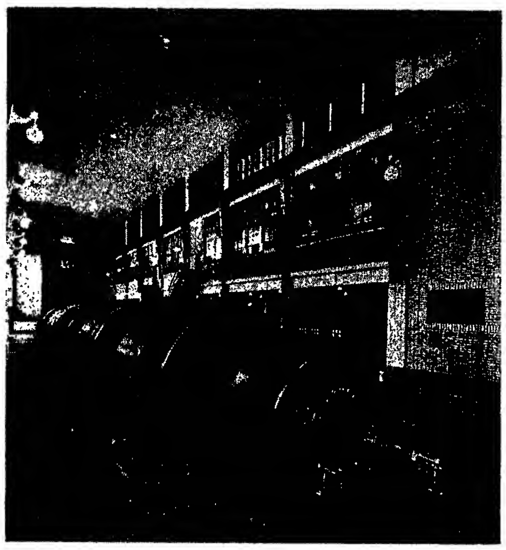

Fig. 9—Variable-Ratio Frequency Converters Showing Regulating Equipment for Induction Unit in the Foreground

of one system is exactly 2.4 times that of the other, the slip frequency will be zero and the excitation to the 25-cycle unit will be direct current. The frequency converters are designed to transmit from zero to 20,000 kw. in either direction with an opposite and simultaneous frequency variation of one-half cycle on each system. This variation will produce a slip frequency of 0.7 cycles per second in the excitation voltage to the 25-cycle unit.

Synchronizing. The closing of the 60-cycle synchronizing breaker, described in a preceding paragraph is shown by a white pilot lamp on the operator's control board. This lamp is lighted and the 25-cycle main line breaker can be closed provided the locking out relays for both the 25-cycle and 60-cycle units are in the reset position, the power factor control rheostat is on the position which gives unity power factor at no load and normal voltage, the brushes on the a-c. exciter are on neutral position, the 25-cycle synchronizing breaker is open and the 25-cycle bus voltage is normal. With the appearance of this light the operator closes the 25-cycle main line breaker which energizes the exciting transformer and completes the connection from the 13,800-volt bus to one side of the 25-cycle synchronizing breaker. As soon as the exciting transformer is energized current flows through the a-c. exciter, thence through the fields of the regulating machine and from the commutator of the regulating machine into the rotor of the induction machine.

At this point voltage begins to build up in the stator of the induction machine. Since the excitation of this machine is derived from the station bus the frequency of the voltage generated in the stator is the same as the frequency of the bus voltage. Correct synchronizing, therefore, depends only upon getting the stator voltage approximately equal to and in phase with the bus voltage. The contact arm of the power factor control rheostat remains on its predetermined "run-off" point until after the 25-cycle synchronizing breaker is closed. The contact arm always returns to this point whenever the 25-cycle main line breaker is opened.

The phase angle of the stator voltage with respect to the bus voltage is determined by the position of the two brush yokes on the a-c. exciter. The direction in which the brushes are shifted to obtain the proper phase angle is determined by the operation of the voltage balancing relay. One coil of this relay is connected across the *A* and *B* phases of the bus potential transformers and the other coil of the relay is connected between the *A* phases of the bus and the machine potential transformers. One set of contacts close to run the brushes in the speed lowering direction (*i. e.*, with rotation) when the machine voltage lags the bus voltage, and the other set of contacts close to run the brushes in the speed raising direction (*i. e.*, against rotation) when the machine voltage leads the bus voltage. A phase angle difference between stator and bus voltages of approximately 10 degrees causes this relay to close contacts.

The rapidity with which the brushes are shifted is controlled by the action of two contactors, device 15-*F* and device 15 *X-F*. The *a* contacts of these two

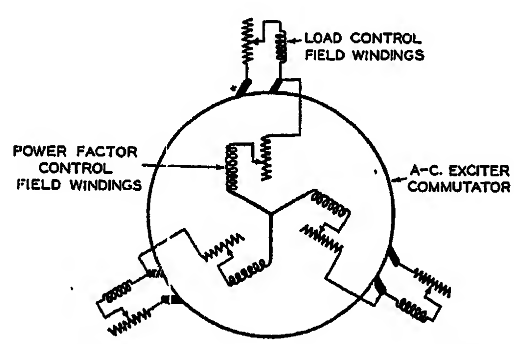

Fig. 10—Schematic Diagram of Field Connections for Scherbius Regulating Machine

contactors are in series with each other and are in series with the contacts of the voltage balancing relay. The connections are arranged so that 15-*F* picks up and drops out with a speed which is proportional to slip frequency. The operation of this contactor causes a shift in the brushes on the a-c. exciter in a direction as determined by the voltage balancing relay.

It may be seen, therefore, that the brushes are shifted with a speed proportional to slip frequency to a position

where the stator voltage is approximately in phase with the bus voltage. A slip frequency of zero indicates that the speed of the unit is exactly correct for the system frequency and that there is no phase displacement between machine and bus voltage. The brushes then remain on neutral and the closing of the 25-cycle synchronizing breaker takes place as soon as the machine voltage builds up to a value which is approximately equal to the bus voltage.

The stator voltage is prevented from rising too high during shifting of the brushes by the voltage regulating relay. With the 25-cycle synchronizing breaker open, the lowering contact of this relay picks up a contactor whose *b* contact interrupts the normal brush shifting circuit and whose *a* contact causes the brushes to return toward neutral. This has the effect of reducing the stator voltage. When the voltage has been reduced to normal, the lowering contact of the voltage regulating relay opens and the normal brush shifting operation is resumed.

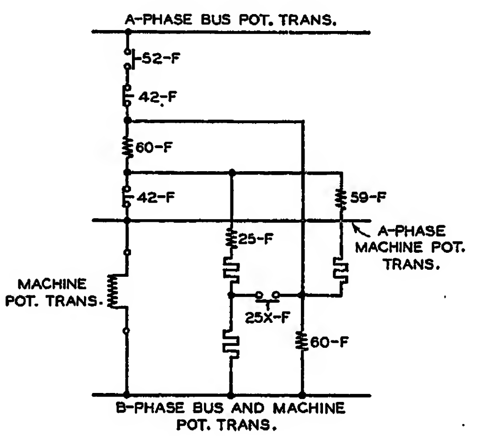

Fig. 11—Schematic Diagram Showing Connections for No. 25-F Synchronizing Relay

25-*F*	25-Cycle synchronizing relay
25*X*-*F*	Auxiliary contactor for 25-*F*
42-*F*	25-cycle synchronous breaker
52-*F*	25-cycle main line oil circuit breaker
59-*F*	Overvoltage relay for 25-*F*
60-*F*	Voltage balancing relay

The actual synchronizing operation is controlled by the action of an a-c. voltage relay device 25-*F* and its auxiliary d-c. contactor device 25*X*-*F*, a schematic diagram of which is shown in Fig. 11. The coil of 25-*F* is connected through two sections of external resistance between the *A* and *B* phases of the machine potential transformer. When the stator voltage rises to 12,000 volts 25-*F* picks up. An *a* contact of 25-*F* picks up 25*X*-*F* which seals itself in. When 25*X*-*F* picks up it short-circuits a part of the resistance in the coil circuit of 25-*F* and causes 25-*F* to be connected between the *A*-phase of the bus potential transformer and the *A*-phase of the machine potential transformer. Its drop out, therefore, is determined by the value of the vector difference voltage between the machine and the bus. This relay is set to drop out at 17 volts secondary or 2,040 volts primary which means that synchronizing takes place at a phase angle difference of approximately 10 degrees or less. The dropping out of 25-*F* causes the 25-cycle synchronizing breaker to close, connecting this unit to the 25-cycle station bus.

Voltage Regulation and Load Control. As soon as the 25-cycle synchronizing breaker is closed the 25-cycle bus voltage is automatically controlled by the voltage regulating relay. This relay, a contact-making voltmeter type, has control of the power-factor control rheostat. The contact circuit of this relay is interlocked with the contacts of two current relays of the contact making ammeter type which limit the current through the unit. One relay is actuated by the stator current and the other by a combination of stator current and a constant current derived from the machine potential transformer to simulate the magnetizing current, the resultant being proportional to the rotor current. This use of a phantom secondary current is made because the frequency of the actual secondary current is too variable for the proper operation of protective devices.

The power factor relay, which is actuated by the stator current and potential, controls the direction in which the power factor control rheostat operates in the event of overcurrent. If the overcurrent is the result of too much overexcited reactive kva. the rheostat is run in the direction which increases the resistance in the field circuit. If the overcurrent is the result of too much underexcited reactive kva. the rheostat is run in the direction which decreases the resistance in the field circuit. The 25-cycle unit can be adjusted to operate at no load between the limits of 24,000 reactive kva. underexcited and 16,000 reactive kva. overexcited and at full load between the limits of 11,000 reactive kva. underexcited and zero reactive kva.

The amount of load transferred through the frequency converters is controlled manually by the switchboard operator. The amount of load transferred under any given condition of frequency spread on the two systems is determined by the amount of brush separation on the commutator of the a-c. exciter. The power transfer is limited to 20,000 kw. in either direction by the action of two power limiting relays whose contacts operate the brush shifting contactors. One relay limits the power transfer from the 25-cycle to the 60-cycle system and the other relay limits the power transfer from the 60-cycle to the 25-cycle system. Both the 25-cycle and 60-cycle buses in the Page Avenue station are supplied through transformers of the load-ratio control type. The 60-cycle transformer banks are equipped with eight 2½ per cent taps in their high-voltage windings and the 25-cycle transformer banks are equipped with nine 2½ per cent taps in their low-voltage windings. The operation of this tap-changing equipment in con-

junction with the reactive kva. requirements of the frequency converters gives a very flexible means of controlling the 25-cycle and 60-cycle bus voltages at the station.

The synchronizing and voltage regulation of the 25-cycle unit may be controlled automatically or manually by means of a control switch. This may be turned to either position at any time while the set is operating. The power-limiting and current-limiting relays are operative during both automatic and manual control of the 25-cycle unit.

The unit is protected against winding failure by current differential relays which shut down and lock out the set. The set is also shut down and locked out by the presence of overcurrent on the high-voltage or low-voltage sides of the exciting transformer.

Ventilation. Although the 60-cycle unit is self-cooled the 25-cycle unit requires 75,000 cu. ft. of air per minute to limit the temperature rise to 50 deg. cent. This is supplied by two blowers located directly underneath the air discharge of the induction motor. The first blower is started by the closing of the 25-cycle main line breaker. The second blower is started at 50 deg. cent. by a thermostat located in the discharge air. All ventilating air is supplied through automatic, self-cleaning filters.

Conclusions

The performance of this equipment during all sorts of system conditions during the past year has demonstrated the feasibility of automatically controlling large frequency changer sets. The stabilizing effect of the 60-cycle high-speed excitation scheme on the voltage during system short circuits and the accuracy and speed of the 25-cycle synchronizing operation are especially noteworthy. Manual synchronizing of the 25-cycle unit is difficult because of the complex character of the excitation system and because of the constantly changing value of the slip frequency. This operation is performed automatically in a very short time with no interchange of power between the two systems, for both zero spread and maximum spread of the two system frequencies.

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Discussion

O. J. Rotty: The authors have given a very clear description of the control scheme employed for the automatic operation of the very complicated requirements of the Scherbius method of frequency changer control. As pointed out by the authors, these machines are located at one of the major interconnecting stations of the company's system. Although operators are required at this station for the various important switching operations, these machines are automatically controlled because experience at other stations has proven the automatic control to be faster, more accurate, and more dependable than manual operation. It is felt by the company's engineers that this is particularly true for machines so inherently complicated of operation.

Although these machines are referred to as being completely automatic they might more properly be described by the popular term, "push-button start and stop." That is, they are started by the operation of a manually operated control switch after which all steps are carried out automatically up to the point where it is desired to bring on the 25-cycle unit when another manual control switch is operated and after which all functions are again automatic. Manual shut-down of an entire set requires only the operation of a single control switch and all apparatus is returned to the normal off-position automatically.

The amount of load transfer through the machines and the reactive kva. carried by each unit are controlled manually by the operator although power limiting and current limiting relays prevent exceeding full load values. The use of load control relays which could be set by the operator for any desired load and which would then definitely hold that load were considered at the time of purchasing the control equipment. However, this scheme was not adopted as it would have prevented the machines from taking full load at times of system trouble (if the relays happened to be operating at less than the full load setting) and it was felt that the feature of the machine automatically going up to full load upon system trouble was very desirable. This has proven out a number of times in actual operation.

It may be of interest to mention that the same scheme as used for indicating synchronism of the 60-cycle unit, as described in this paper, is now being installed for automatically closing the oil circuit breaker of the 132-kv. transmission line supplying this station from the Osage plant, and in time it is intended to employ the same scheme for automatically closing other important transmission line breakers.

Forecasting Population for Engineering Purposes

BY JAMES N. HOLSEN[1]
Non-member

ENGINEERS and persons responsible for the management of engineering projects have a common interest in problems of forecasting population growth and market demands. The soundness of engineering projects depends upon their capacity to fulfil a real demand. Unsoundness, or even failure, may result from planning and designing engineering projects without regard to industrial and population trends. Similarly city planning, housing and home building projects, educational and social programs of various kinds, should ordinarily be based upon the number of people to be served at some future date and their economic and social characteristics.

Practical Value of Population Forecasts

Within the Bell System the careful study of factors influencing the growth, distribution, and character of the population is regarded as essential to the intelligent planning of the telephone business. In planning extensions to the telephone plant, engineers are provided with forecasts of the probable telephone service requirements at periods ranging from five to twenty-five years in the future. These forecasts are based upon the probable growth, distribution, and character of the population. On the basis of these forecasts of probable telephone service requirements and other pertinent factors, engineers determine the initial and ultimate size of buildings, switchboards, underground cables, and the pole lines and aerial cables. Thus, vastly more depends upon the forecasts than the mere provision of telephone instruments, which subscribers are apt to regard as the principal part of the telephone plant. In planning for the future the central aim of the telephone company is to supply the right amount of facilities in the right place. Manifestly, this cannot be done except when based on dependable forecasts of population and its distribution.

Because of the need for reliable forecasts in the telephone business, the American Telephone and Telegraph Company and its various operating companies have given considerable attention to population facts and the interpretation of population changes. It is realized, of course, that population forecasts are subject to the same possible errors as are always present where the human element is an important factor. Unlike the movement of stars which can be predicted by astronomers to within a fraction of a second, the course of human activities does not lend itself to precise foretelling. However, the experience of the telephone company has been that population forecasts can be made with a very helpful degree of accuracy, thereby making for maximum economy in the extension of the telephone plant.

Basic Considerations Involved

Several mathematical formulas have been devised on the assumption that future population can be determined from past trends by the mere application of figures in the formula. It is believed, however, that such formulas place too much emphasis on past trends and ignore the fact that new influences are always appearing and that old influences are frequently ceasing to be of importance. They also tend to give a sense of security to the use of an estimate which is unwarranted by the basic assumptions which have been made. Obviously, it is always well to study the past, but it is never safe to assume that the future will reproduce the past.

Cities and regions grow not from mere wishing or boasting, but usually because of definite geographic and economic advantages which enable them to develop population supporting activities in competition with other localities. Forecasts are apt to miss the mark rather widely if the forecaster has only a local point of view. From a local standpoint, there may appear to be very good reasons why a region should make great advances agriculturally; from a national standpoint, it may appear more reasonable to expect a contraction in its agriculture. Similarly a town may appear to be an ideal location for a particular line of manufacturing; but if a competing town is better situated in respect to raw materials and markets, and if it offers cheaper power and a better labor situation, then the advantages of the first town are likely to be of little avail. The national outlook eliminates the optimism based on the pride of those born or residing in the particular locality for which the forecasts are being made, and the conclusions reached by a broad point of view undoubtedly are much more likely to be realized. Dependable population forecasts cannot be based upon what should or could be done; they must be based upon what most probably will occur.

Population of the United States as a Whole

Because communities are competing with each other for the population growth of the United States as a whole, population forecasts for States and for individual cities should be made with due regard to population trends of the country as a whole. Some of the facts and tendencies that have a definite bearing upon the population growth of the United States briefly may be summarized as follows:

1. The United States is almost certain to continue a

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1. Southwestern Bell Telephone Co., St. Louis, Mo.

Presented at the South West District Meeting of the A. I. E. E., Kansas City, Mo., October 22-24, 1931.

restrictive immigration policy for many years to come. Until the last decade immigration contributed heavily to our population growth. This is clearly evident from the 1930 census figures, which showed that foreign-born whites and their children constituted 31.1 per cent of the country's total population. In the future, population increases must depend more and more upon the excess of births over deaths.

2. The birth rate in the United States has been declining gradually for several years, due to such factors as generally higher living standards, smaller living quarters, marriages in which both husband and wife are breadwinners, the tightening of immigration restrictions against the prolific races, and finally wider knowledge and utilization of birth control information. Although there have been reductions in infant mortality, the effect has not been sufficient to prevent a decline in the rate of natural increase. For example, in 1910 the birth rate was about 30 per 1,000 population and the death rate was 15, while at present the birth rate is very close to 19 and the death rate about 12. Thus, in twenty years the margin which represents natural increase in population has decreased from 15 per 1,000 to 7.

The number of people in Continental United States in the last forty-year period together with increases in each ten-year period is indicated below:

POPULATION OF CONTINENTAL UNITED STATES

Year	Total	Increase during previous decade	
		Number	Per cent
1890 (June 1)	62,947,714		
1900 (June 1)	75,994,575	13,046,861	20.7
1910 (April 15)	91,972,266	15,977,691	21.0
1920 (January 1)	105,710,620	13,738,354	15.0
1930 (April 1)	122,775,046	17,064,426	16.1

The gain during the 1920-1930 decade exceeds by more than one million the largest previous gain, that occurring in the period 1900-1910, and it is 3.3 million in excess of the growth realized in the decade just preceding, that is, from 1910 to 1920, when the net immigration was 25 per cent greater and the rate of natural increase some 10 per cent higher. A partial explanation of this seeming inconsistency is in the probable greater efficiency with which the 1930 count of inhabitants was made. Due to the better selection, training, and higher compensation of the 1930 enumerators, they probably did a better job of counting, also, the 1930 census was relatively more accurate because of the better rural roads, more extensive telephone service, the policy of permitting recounts, and better organization and supervision of the over all undertaking. Furthermore, the period of counting of the 1910-1920 decade was some six months shorter than that of the 1920-1930 decade. It seems evident that the natural rate of population growth has been steadily slowing down, and that the same general tendencies will prevail over the next twenty years.

Now the slackening in the rate of population growth for the country as a whole will naturally be reflected in the population increase to be divided among the urban and rural communities making up the total population. Unless a community is relatively better situated than in the past, it cannot expect to maintain its past rate of growth. In order to hold its natural rate of increase, the population supporting activities of a community must expand proportionately. In order to increase at a higher rate, its advantages must be such as to attract population at the expense of less favorably situated communities.

There is one factor which lends emphasis to the general statement that a community must be relatively better situated to maintain its past rate of growth, and this consideration is the increasing mobility of the American people. Population in the United States has always been highly mobile; that is to say, the American people have been peculiarly ready to move in response to economic activity, including the opening of new lands for agriculture, and other attractions. But the point is that the development of improved means of communication and transportation and the spread of information concerning the relative advantages or disadvantages of this or that part of the country as a place in which to live and labor have accentuated this mobility. Because of this the real adtanges or disadvantages of communities are likely to play a larger role than heretofore in determining their relative capacities to attract or to hold population.

Urban population has been increasing at a far higher rate than rural population. During the past decade the increase in the rural population was 2.4 millions as against 14.6 millions for the urban centers. Whereas the 1900 census reported only 40 per cent of the population as urban, the corresponding figure in 1930 was 56.2 per cent. The city-ward tendency in population, which is nation wide and regarded by some as a dangerous trend, is intimately related to fundamental economic changes, including (1) the capacity of the farms to maintain a rapidly increasing urban population, aided by the constant development of labor-saving machinery, including farm tractors and scientific agriculture, and (2) the transfer to the cities of many labors that were formerly a part of farm work. Contributing factors lie in the tendency of our export trade to shift from raw materials to manufactured commodities, the increasing per capita demand for manufactures in this country as a result of the rising standard of living (a tendency that is temporarily obscured by the present general business depression), and also in the additional opportunities for untrained workers in the cities, brought about by the decrease in the foreign labor supply after the drastic restrictions on immigration went into effect and by the unusual growth in the service industries.

Further scrutiny of the census figures indicates that the larger cities in the country are growing more rapidly than the smaller cities. Individual exceptions to the

general rule may of course, be found. Between 1920 and 1930 the total growth of the ten largest cities in the United States, including their suburban territories, accounted for approximately 40 per cent of the total population increase of the country. The entire group of cities of over 10,000 population obtained 68 per cent of the country's total increase; and if the suburban areas of the cities over 50,000 were included, the proportion is raised to 86 per cent.

Not only has urban population been increasing at a far higher rate than the rural population, but the tendency is one that probably will continue in the future. Looking ahead to 1950, one sees little reason for estimating a materially larger farm population than at present. There will doubtless be substantial farm losses in many sections of the country. Also the group of smaller towns and cities, say those below 5,000 population, probably will increase but slowly. All present indications point to the probability that substantially all of the country's population growth will be absorbed by the group of cities of over 10,000 population and the smaller communities tributary to metropolitan centers.

Purpose and Value of Economic Surveys

The specific population forecasting job of the Southwestern Bell Telephone Company involves individual forecasts for some seven hundred towns and cities in which it operates, scattered throughout the States of Missouri, Kansas, Arkansas, Oklahoma, and Texas. Inasmuch as its long-distance lines serve either directly or through connecting with the lines of other telephone companies virtually every section of these five States, the job includes also forecasts of the probable population of various regions or sections of each State and for each State as a whole.

With a view to providing a more or less definite picture of economic conditions and trends in its territory, the Southwestern Bell Telephone Company inaugurated a series of economic surveys covering the five States in which it operates. The first of these studies was made in 1924 and the last of these completed in 1930 just prior to the 1930 census. It is planned to check the statements and forecasts from time to time against the conditions realized and to correct or supplement them as may appear advisable. The general plan of these studies involved an analysis and presentation of the following subjects:

1. Natural features, including a study of land form, soils, climates, vegetation, and water resources, with respect to their influence on activities.

2. The situation and outlook of the State's basic industries—agriculture, manufacturing, lumbering, and mining—in relation to population.

3. The comparative conditions and prospects in the various natural or economic-geographic regions of the particular State, the regional treatment being essential because of the dissimilarity of conditions prevailing over most States.

4. A detailed analysis of the situation and outlook of the principal cities.

5. The effect of the probable population changes on the demand for telephone service.

Illustrative of the kind of questions for which answers were sought by the State economic surveys are these:

How will the expansion (or perhaps contraction) of agriculture be distributed over the State? Will farmers have a greater or lesser purchasing power? What is the manufacturing outlook in the State? What kind of manufacturing activities may be expected to expand and what about their localization? Will the increase in the population-supporting activities be sufficient to cause the State to attract large numbers of persons from other States?

Since the answers to such questions influence directly the planning and management of the telephone business, the company engineers responsible for the population forecasts necessarily dealt with hard facts and figures; they recognized that reliable forecasts could not be made if unfavorable conditions and undesirable tendencies were ignored and only the bright side were stressed. Always they attempted to maintain an unprejudiced position, recognizing that many parts of the country possess advantages as fields for the employment of labor, capital, and executive ability, and that localities are in competition with one another for shares of the country's total population growth.

The organization for making the surveys and preparing the reports was small. Before issuing the final report the manuscript and the population and telephone forecasts were carefully reviewed in group conference. Personal inspection tours of each state were considered essential. Before making such trips it was considered desirable to collect and review carefully such information as was available on the particular area to be covered. Working diagrams and maps were prepared and the various chapters of the report were tentatively sketched. This procedure usually revealed conflicting statements as to matters of both fact and of opinion, thereby indicating some of the things to be cleared up during the inspection trip. This preliminary study also revealed gaps in the information which needed to be filled. Obviously, such a procedure was necessary in order to obtain maximum results from both the observation and interview work involved in the inspection trip.

Prior to the field trip, working contacts were established with the State University and the State College of Agriculture, with the department heads of the State government, and with the agricultural and industrial departments of the railroads operating in the State. Throughout the conduct of the job, valuable assistance was rendered by various Government Bureaus in Washington.

During the field inspection trips, interviews were had with persons in many lines of work, including State officials, University and College professors, agricultural experiment station directors, bankers, manufacturers

and distributors, county agents, representatives of associations of various kinds, and also with local representatives of the telephone company. Of course, all the materials and suggestions gathered in this manner could not be accepted at their face value, because local pride and enthusiasm were not always carefully restrained. However, it was usually possible to detect misinformation and prevent it from coloring the final appraisals and analyses. Apart from furnishing information, a considerable number of persons volunteered or were asked to criticize sections of the report, and their cooperation in this regard helped greatly to reduce the number of erroneous statements and conclusions in the final report.

The formal reports which present the findings and conclusions, vary in length from 150 to 275 pages, depending partly upon the complexity of the problems encountered. It was found desirable to describe the conditions encountered and present the line of reasoning upon which each conclusion was based. Thus the reports can be readily checked and supplemented whenever it is desirable to do so. Readability as well as accuracy was sought. Maps and charts were freely used in the reports, and much of the discussion was centered about them. The subjects covered by the maps and charts of the "Economic Survey of Texas" included the following.

- Regional Comparison of Area, Population, and Number of Telephones, 1928 and 1950.
- General Land Form Features.
- Distribution of Rainfall.
- Native Vegetation.
- Irrigated Areas and Principal Artesian Belts.
- Maps showing details of the various natural regions in Texas.
- Population Changes by Regions, 1920 to 1928 (estimated).
- Net Interstate Movement of Population in and out of Texas, 1900-1910, 1910-1920.
- Population Density by Counties, 1928 (estimated).
- Per Cent of Farm Population Colored by Counties, 1925.
- Foreign-born White Population as Per Cent of Total by Counties, 1920.
- Per Cent Illiterate in Population 10 Years of Age and Over, by Counties, 1920.
- Telephones Per One Hundred Population (Texas compared with Missouri, Kansas, Oklahoma, Arkansas, and Total United States) 1905 to 1928.
- Telephones per 100 Population, by Exchanges, 1928.
- Per Cent of Farms Having Telephones, 1925.
- Trend in Acreage of Principal Field Crops, 1900 to 1927.
- Trend in Number of Live Stock, 1900 to 1927.
- Per Cent of Land Area in Harvested Crops, by Counties, 1924.
- Average Value of Farm Lands and Buildings Per Square Mile, by Counties, 1925.
- Average Value of All Farm Property Per Farm, by Counties, 1925.
- Per Cent of Farms Operated by Tenants, by Counties, 1925.
- Change in Number of Farms, by Counties, 1920-25.
- Distribution of Cotton Acreage, by Counties, 1925.
- Trend in Cotton Production (World, United States, and Texas) 1900-1927.
- Series of figures showing distribution of live stock and principal farm crops.
- Approximate Per Cent of Land in Forest and Woodland, by Counties (East Texas), 1925.
- Sketch Map Showing Location of Principal Minerals (Other than Oil and Gas).
- Petroleum Production, 1896-1927.
- Trend in Oil Production by Major Districts, by Months, 1926-1928.
- Principal Manufacturing Industries (Establishments and Wage Earners) 1925.
- Wages Paid Per Wage Earner in Principal Manufacturing Industries, 1925.
- Average Number of Wage Earners Engaged in Manufacturing, by Counties, 1925.
- Number of Active Cotton Spindles (United States, the South and New England, 1880-1927).
- Location of Cotton Mills in Texas, 1928.
- Railroad Mileage in Texas, 1870-1926.
- Railroad Construction in Texas Lines, 1925.
- Map of Texas Illustrating Changes in Freight Rate Making Practises.
- Trade Territories as Indicated by Bank Relationships.
- Trade Territories as Indicated by Toll Traffic.
- Trade Channels Between Texas and Mexico.

It is, of course, too early to determine the accuracy of the 1950 population forecasts made for the States and for the individual cities and towns. Obviously, many uncertainties attend the making of forecasts of this kind. That the population and market guide posts established by the surveys are of considerable value has, however, been thoroughly established. As previously indicated population forecasts were made for future years. It may be of interest, therefore, to compare the 1930 estimates with the 1930 census returns. In the tabulation below the estimates for January 1, 1930 have been projected to April 1, 1930, the census date.

	Census returns 1930 (April 1)	Economic survey estimates 1930 (April 1)	Per cent difference
Missouri	3,629,367	3,626,000	0.09
Arkansas	1,854,482	1,850,000	0.24
Kansas	1,880,999	1,864,000	0.90
Oklahoma	2,396,040	2,378,000	0.75
Texas	5,824,715	5,777,000	0.82

Forecasting the Population of a City

By the nature of things, no two cities present situations precisely alike. Indeed, one of the most striking facts is their dissimilarity. However, in analyzing the past growth of a city and in forecasting its future, there are usually five principal influences to be considered:

1. Size and character of its tributary trade territory.
2. Its industrial expansion.
3. Its attraction as a home center.
4. Governmental activities.
5. Institutional activities.

1. Study of the trade territory of a city is essential to an analysis of the population supported or likely to be supported by the wholesale, retail, and general office business of a city. There are various grades of trade centers, grading upward in order from cross-road stores, hamlets, villages, towns, county-seat towns, small cities,

minor cities, major cities, to metropolitan cities. All grades of trade centers function as agencies both for the outward distribution and the inward collection of goods. The typical cross-roads store, for example, may distribute only such articles as are in general demand by a small farming population and serve as a collection agency for, perhaps, only the surplus production of butter and eggs of nearby farms. At the other extreme are the metropolitan cities with varied and far flung distribution, and collection agencies of the type which make them great primary markets for such commodities as grain, cotton, or livestock.

The term "trade territory" is often used rather vaguely. Sometimes it is used to designate the territory tributary to the retail business of a city; and at other times, it may refer to the territory tributary to the wholesale business. For the smaller towns and cities the term is less subject to confusion, since the wholesale business is, in most cases, negligible. The larger cities, however, ordinarily hold a dominant place in the jobbing and wholesale trade of a zone that reaches far beyond the territory served by its retail stores. The metropolitan cities may even have a nation-wide distribution for some commodities. Also, it should be recognized that what is usually designated as the trade territory of a city is seldom, if ever, exclusively its own, for trade territories are over-lapping.

However, for purposes of analyzing the past and probable future, of the wholesale and retail business of a city, its trade territory can usually be defined with sufficient clearness. Aids in this include the analysis of banking relationships, newspaper circulation, and the distribution of sales of representative wholesale establishments. The analysis of the long distance telephone traffic in a number of States has largely confirmed the ideas of the respective trade territories of the principal cities as obtained by the examination of other data.

Many cities have had a rapid growth as trading centers along with the development of a tributary territory which has been settled rapidly. On the other hand, where rival trading centers have developed within the territory formerly tributary to a city, or where the territory has ceased to grow, then the importance of the city itself as a trading center has diminished. The trade territory of practically every city is changing, increasing or decreasing in extent and also undergoing changes in the character of the population. In respect to the latter, it should be remembered that the importance of a trade center depends not only upon the number of people in the tributary area but also upon their standard of living. Low living standards are unfavorable to the development of sizeable trade centers; while high living standards, in housing, furniture, vehicles, clothing, recreation, make for numerous and large trading centers.

In an analysis of the probable future changes in the trade territory of a city, consideration must be given to the trend in agriculture and industry, to such factors as improved highways, motor trucking, and changes in freight rates. For example, it seems clear that improved roads and the use of the automobile will continue to diminish the importance of many small towns.

2. Giving full value to the probable more intensive development of many sections of the country it now appears that the growth of most of our cities during the next twenty years will be due primarily to their relative attractiveness for industrial expansion.

For purposes of population analysis, it is helpful to classify industries. Industries may be grouped according to those which attract population, such as steel mills and automobile factories, and those which result largely from the presence of population, for example, bakeries, laundries, and ice cream factories. Obviously, the growth of industries of the latter type must depend upon the increase in the population of the particular communities which they serve, or upon an increased per capita demand. Again, it is helpful to consider industries from the standpoint as to whether they are conservative or exhaustive in nature, that is, whether their supplies are continuous or temporary. The lumber industry, as it has been carried on in this country, is a striking example of an exhaustive industry; many towns have either become extinct or else greatly declined in population when their lumber industries have moved on following the exhaustion of tributary lumber supplies. In many places, industries based upon the presence of minerals are exhaustive. For example, if a city is supported mainly by oil refining, and if the refining industry depends upon a single oil pool, the time will almost certainly come when the city's population will be greatly reduced unless other population supporting activities are developed.

If a city has diversified manufacturing plants, its growth is likely to be more uniform or stable than for a city where a single industry is dominant. A one industry town may have a rapid growth or a very slow one, depending on whether the industry is prosperous, or the reverse. It is well to note the different industries do not contribute to the population of a city in exact ratio to the number of employees. In a number of industries, including the manufacturing of shoes and clothing, a large proportion of the workers are girls and women, representing second and third members of a family. Further, one must consider the effects of labor saving machinery. In the past virtually all industries have been able to increase their output by the application of labor saving devices, without a proportionate increase in the labor required, and it is certain that this tendency will continue. Thus the industries of a city may increase their output materially, without a corresponding increase in population.

3. There are many people who choose a place to live rather than a place to work. Among these are the independently wealthy, the retired, and the adventurers. These people seek living conditions to meet their desires and adjust their occupations, if necessary, to what is attainable where they choose to live. Thus

large numbers have gone to certain cities because of climate, to other cities because of amusements, and almost every city, large or small, attracts some from the nearby sections because of city conveniences in general.

The classes who seek places to live first and occupations afterwards are likely to increase in the future. As wealth accumulates in the United States, the number who can live on the income from investments will grow. Cities and towns offering special advantages as home centers are likely to attract a larger proportion of the retired element than formerly, owing to the increasing tendency of this class to go longer and longer distances from their original home.

4. The national capital and many of the State capitals owe their growth primarily to the activities of the Federal or State governments. Governmental business requires a certain clerical force which tends to increase with the development of the country or the state, and with the complexity of the governmental machinery. The late war gave an abnormal impetus to the establishment of new departments and to centralization in general. In the past there has been a general tendency to enlarge the functions of governments, but for the immediate future it seems reasonable to expect an increasing pressure for more economical governmental administration expansion.

5. Many cities in the country have military establishments, educational institutions, penitentiaries, etc., which add considerable numbers to the population. Sometimes institutions of this character are relatively so large and are subject to such wide fluctuations in size, that they tend to render past rates of growth of the city misleading and to make forecasting of the future extremely difficult. In analyzing the population growth of such cities, it has been found advisable to isolate the past population related to institutions and treat this influence separately in forecasting the future.

Many cities possess the advantages just described in more or less equal measure, yet their past and prospective rates of population growth vary widely. It is here that well directed efforts on the part of various civic bodies are important. The community which effectively advertises its natural advantages of location is likely to grow, while a neighboring city equally well situated may stand still or even decline. Civic spirit is, therefore, a proper consideration in every population forecast. Through advertising activities a few of our cities have attracted a larger population than they can hold, and the slump which is bound to follow will perhaps permanently injure them. On the other hand, some cities have probably retarded their growth by advertising which so glaringly exaggerated their attractiveness that their real advantages were overlooked.

In the telephone business, and in most other businesses where advance planning is required, it is important not only to know the probable growth of population, but also its character and distribution, and its division into family units. Future population growth is forecasted upon the basis of certain definite factors already referred to, including expansion of industry or commercial activities which support population. In estimating the amount of population that probably will be located in high grade, medium grade, and poor sections of the city, it is essential to know rather definitely the class of population which is supported by the various activities. Obviously, if, in a particular city, population growth is expected to result from expansion of industries which employ principally common labor, both the character and distribution of the population will be quite different than if growth results from, say, an increase in wholesale and general office business. Similarly, character and distribution will be different if the growth comes mainly from an increase in population of the wealthy retired class. Further, it is well to note that each part of a city is in competition with other sections of the city for the limited population growth of the whole community in much the same manner as cities compete with each other.

Conclusions

Population forecasts, when carefully and intelligently made, serve a valuable purpose in helping to direct the employment of labor and capital to places or projects where they are most needed. What will most probably occur is always the first consideration in population forecasting. Sound forecasts cannot be made to rest upon a local point of view; national factors are always involved, frequently they are international. In boom periods it is necessary to guard against the tendency to overestimate, while the reverse is true of dull periods. Because of the fundamental influence of economic and geographic factors in determining the population growth of cities or regions, the economic survey is invaluable in determining the probable future number of people in a particular city or region, and their social and economic characteristics. Meticulous precision is impossible in making long range population forecasts, but it is both possible and practicable to obtain a valuable working knowledge of conditions in the future.

Discussion

Seymour H. Cronk: After a consideration of Mr. Holsen's paper, I am impressed with the importance of one of his implications. This is, that most engineering cannot be an exact science because of the variable nature of the basic assumptions which it is necessary to make before preparing plans for specific projects. These assumptions usually involve population and marketing in one form or another.

The present depression has emphasized to many minds that a given engineering expenditure would be better apportioned in almost every case if money spent in the preparation of specific plants were limited, if necessary, to the bare essentials and more money were spent in economic research bearing upon the basic assumptions involved.

If there is any measure of truth in the statement of Dr. Wright, President of the A.S.M.E., that the Engineering profession should share in the blame for the present depression because of its part in throwing production out of balance with consumption and distribution, then there is a real need for a closer liaison between economics and engineering.

The purpose of this discussion is to make the point that, according to my observation of engineering trends, the Bell System has for some years been concerned more and more in establishing as reasonably and precisely as possible the basic economic and social assumptions allied with each project for which money is to be spent.

An economic study and estimate which we are completing for Kansas City, Kansas, and which illustrates the economic work done in connection with exchange planning is given in the following.

The Kansas City economic study and estimate will form the basis for the technical plans and will be used to indicate the proper ultimate location and size of new central office buildings, and the best location and size of conduit to be installed under the streets. If plant is to be installed for best service and economy, it must be placed so as to be adequate without being wasteful over a period of at least twenty years.

So the economic problem was to reconstruct Kansas City by blocks on paper as nearly as possible as it will be twenty years in the future. The value of the state economic survey with its population estimates and analysis of industrial trends is obviously great in such work. In Kansas City, all present building development, telephone development, and population or "family" data were recorded by blocks. The amount of vacant and available land was listed by blocks, and these "availability" data were even supplemented by aerial photographs. Past population trends by enumeration districts were studied, and the probable future of each of the controlling industries was studied. All factors were considered which might at this time give any indication of what population and building distribution might be expected in Kansas City in 1951.

To arrive at the final result, which was a detailed growth forecast by blocks, required about 5,000 hours of engineering and economic work.

A less carefully based estimate might be made in a few days' time by other and less thorough methods.

The reason for doing this work in Kansas City, Kansas, and proportionate amounts in other cities, is of course, that the telephone industry has found this, in the long run, to be the cheapest way of "balancing production with consumption and distribution."

D. C. Jackson, Jr.: This paper is a valuable addition to engineering literature, since the matters outlined in it are generally applicable, not merely to any particular type of engineering work, but are generally of use in any field of endeavor having to do with the public.

Of the five points in the general plan of the economic surveys made by the Southwestern Bell Telephone Company, four are of importance to any organization, whether or not of an engineering nature, provided it has a reasonably widespread field for its product. To recapitulate, these points are:

1. Natural features.
2. Situation and outlook of the state's basic industries in relation to population.
3. Comparative conditions and prospects in the natural economic-geographic regions.
4. Detailed analysis of the situation and outlook of the principal cities.
5. Effect of the probable population changes on the demand for telephone service.

I have looked over the report of one of these surveys, that of Kansas, and it is clear that the four parts of this report which correspond to the first four points which I have just named are generally applicable to any large scale project or development of a business or engineering nature.

Tape-Armored Telephone Toll Cable

BY C. W. NYSTROM*

Associate, A. I. E. E.

Synopsis.—Telephone toll cables buried directly in the earth are coming into increased use. The cables are not installed in the more usual clay conduit but are protected by layers of paper, jute, and steel tapes. The experience of the Southwestern Bell Telephone Company in installing some 500 miles of buried cable is described.

* * * * *

TOLL cables in this country have in the past been installed either aerially on pole lines or underground in clay conduit depending largely upon the number of cable units needed to meet service requirements over a given period of time. In those parts of the country where relatively few cables will suffice to meet toll needs for a long period of time, it is usually more economical to employ aerial cable rather than underground cable in conduit. While there will continue to be a definite field of use for aerial toll cable particularly where difficult subsurface conditions obtain, there are many toll routes where ground conditions are favorable on which one or two cables will serve all needs for a long period, and it is for this type of case that tape-armored cables were developed as an alternative to aerial cable.

The cable is termed "tape-armored" because of its outer protection. Lead-sheath cable of the type ordinarily used for toll service is first covered with a wrapping of paper followed by two layers of jute roving. Two steel tapes, one over the other, are then applied, each tape being two inches wide and forty-one mils thick. A separation of one-half inch is maintained between adjacent turns of the tape, and the outer layer is so placed that it covers the space left between the windings of the inner layer. Two wrappings of jute cover the tape. The lead sheath, paper, jute, and steel tapes are thoroughly coated with an asphalt compound; the completed cable is given a coat of whitewash to prevent adjacent layers from sticking together on the cable reels. Such a cable of so-called full size has a diameter of 3¼ in. and a weight of 11.3 lb. per ft. as compared with the 2⅝-in. diameter and 8-lb. weight of unarmored cable.

Buried tape-armored cables possess several advantages over cables carried on pole lines or in underground conduit:

1. Easements for buried tape-armored cable on private rights-of-way may sometimes be obtained more cheaply than for pole lines, as the use of the land for ordinary agricultural activities is not disturbed.

2. Induced currents from paralleling power lines are appreciably less than in unarmored aerial or underground cables, due to the shielding effect of the steel tapes.[1]

3. Cable may be laid to follow the contour of rough country and have sharp bends to avoid obstructions while conduit must have a fairly even grade and long radius curves to permit cable being pulled through it.

4. Manholes are required at spacings of from 500 to 700 ft. if conduit is provided, while with tape-armored cables, manholes may be omitted except at loading points which normally occur at 6,000-ft. intervals.

On the other hand tape-armored cables may have some objectionable features. As they are buried directly in the earth, the location and repair of troubles are generally more difficult and expensive than for aerial cables; however, improvements in methods for maintaining buried cables should reduce such costs, and in any event, the amount of trouble per cable-mile may reasonably be expected to be much less than on aerial cables because of their security from damage by storm, fire, bullets, etc.

The first tape-armored toll cable in this country was installed by the Southwestern Bell Telephone Company. Other telephone companies have since placed similar cables but in view of the writer's greater familiarity with work in the Southwestern Bell territory, this paper will deal, in general, only with that Company's experiences.

One of the first considerations following the decision to place a cable is the selection of the route. Between Fort Worth and Cisco, Texas, where the first tape-armored cable was placed, the country for some 15 miles west from Fort Worth is rolling, with hills gradually increasing in height. For the remaining 85 miles the topography becomes extremely rugged with large quantities of rock found in the soil and the country is covered with dense growths of scrub oak and other underbrush. Roads are few and accurate maps were not obtainable. The difficulties and time required in making a detailed ground survey were such that it was deemed advisable to photograph the general route from an aeroplane. From the photographs so obtained a tentative route was marked out and found to be of considerable assistance in expediting the ground survey which is, of course, necessary in any event. With fairly open country, frequent roads and adequate maps, there ordinarily would be no necessity for a preliminary aerial survey.

With regard to right-of-way for tape-armored cables, it is generally felt that private property is more desirable than public highways where road improvements such as straightening, widening, grade changes and reroutes

*Southwestern Bell Telephone Co., St. Louis, Mo.

1. *Trends in Telephone and Power Practise as Affecting Coordination*, by W. H. Harrison and A. E. Silver, A. I. E. E. TRANS., June 1931, p. 437.

Presented at the South West District Meeting of the A. I. E. E., Kansas City, Mo., October 22-24, 1931.

might necessitate expensive relocations of cables. On the other hand, if private property easements are high in price or not obtainable or construction costs on privately owned land are too great, it might be best to place cable on the highway and so located as to be subject to the least probability of having to be moved. It is evident that the question of the best possible location for the cable is one requiring careful consideration.

The Fort Worth-Cisco and other tape-armored cables placed later are largely on private rights-of-way, in many instances in cultivated fields. The transportation of five-ton reels of cable over soft and often muddy ground is not usually possible with an ordinary truck or cable reel trailer and it was necessary to design a suitable outfit. Fig. 1 shows the caterpillar type of trailer used as well as a commercial type of tractor necessary to haul the cable to its proper location. There have since been some developments in the line of four-wheel drive truck equipment for handling the deliveries on the right-of-way as well as on the highway.

The equipment in Fig. 1 while ideal for use on soft or uneven ground, is not suitable for hauling cable over

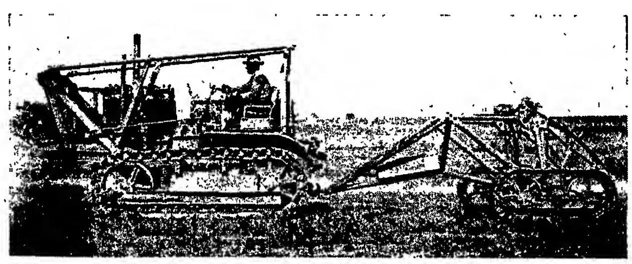

FIG. 1—CABLE REEL TRAILER AND TRACTOR

long distances because of its limited speed. Some of the hauls on the Fort Worth-Cisco route were as long as twenty miles from the nearest railroad siding and for such cases a rear-wheel drive truck with special winch and body equipment made fairly high speeds possible on highways.

For trenching in earth a commercial wheel type excavating machine was first used and proved quite satisfactory until soil containing considerable quantities of rock was encountered. This rock lay just below the ground surface and while not in solid ledges, was so hard and in such quantities that the trenching machine could not function. After some experimenting and changes in design the plow shown in Fig. 2 was found to answer the needs quite satisfactorily. For solid rock or where the rock formation was such that the plow could not break through, pneumatic drills and blasting were required.

The cable may be laid in the trench directly from the reel. Where this method is impracticable, as, for example, cables crossing under paved highways, pipe lines or placed on steep slopes, the cable may be pulled over rollers placed on the bottom of the trench. Backfilling was then done by a machine of the type shown in Fig. 3.

The use of the rock-breaking plow focused attention on the further possibility of using a plow for both trenching and laying cable. This led to the development of an outfit which not only dug a trench, but laid the cable in it and backfilled the excavation all in one operation. The result was the plow pictured in Fig. 4. This plow after laying more than 300 miles of cable is still in good condition. The equipment

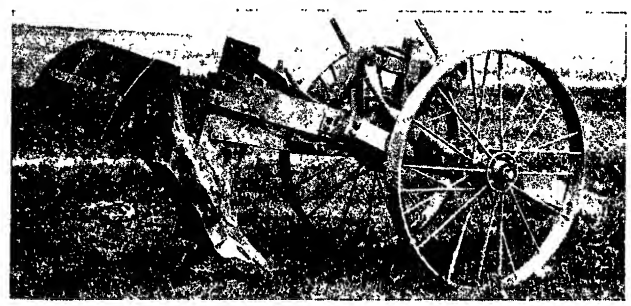

FIG. 2—ROCK-BREAKING PLOW

consists essentially of two main parts, a chassis and a vertical central portion which may be raised or lowered to bury the cable at depths up to 28 inches. Fig. 5 shows the lower portion of the mechanism and Fig. 6 the complete cable laying equipment in operation. In connection with the latter figure it will be noted that the plow does not dig a trench, properly speaking, but merely cuts a slot through the ground. Some earth is thrown out and this is drawn to the center of the slot by the backfiller. If desired, a tractor may be run over the disturbed earth to pack it down.

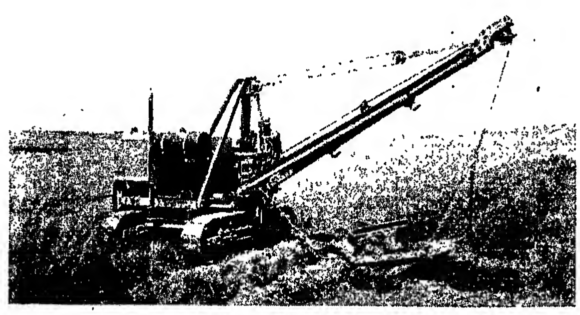

FIG. 3—TRENCH BACKFILLER

Two tractors, sometimes three, are required to pull the cable-reel trailer, plow, and backfiller. As can be seen, the cable passes from the reel through a pipe extending into the ground. Thus as the plow proceeds the cable is deposited at the bottom of the trench and is not dragged through the ground at any time. The essential features of the plow are more clearly seen in Fig. 5. The forward or cutting end is a steel plate having a sharpened edge and a shoe is provided at the bottom to make a larger space for the cable. Side

plates are welded to the cutting blade and to the outer sides of the pipe through which the cable passes.

Small boulders and tree roots often made progress very difficult for the cable laying plow. It was found

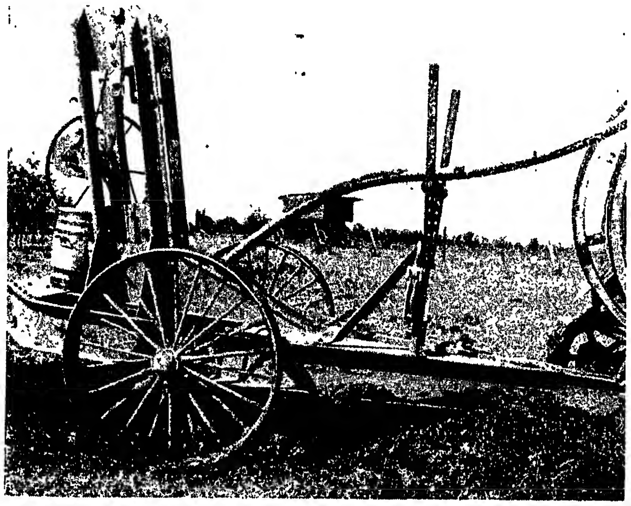

FIG. 4—CABLE LAYING PLOW—IMPROVED DESIGN

that with a slot first cut through the earth, the plowing in was considerably expedited and cable was laid in locations where successful plow installations seemed, at first, very doubtful. The plow used for this purpose is called a "rooter" plow. The rooter first used was similar to the rock plow of Fig. 2. In fact it was the same plow with the mold boards removed and a curved forward cutting edge added. The first rooter plow was found to lack in requisite strength and following the building of the second cable plow, Fig. 4, the rooter shown in Fig. 7 was designed. This fits in the same chassis as the cable laying plow. Thus either the cable

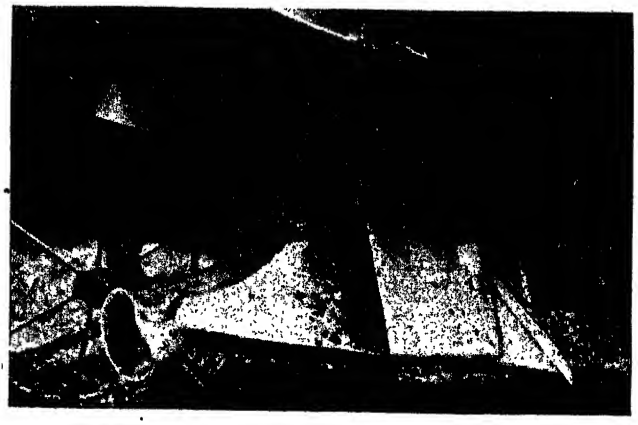

FIG. 5—LOWER PART OF CABLE LAYING PLOW—IMPROVED DESIGN

laying or rooter plowing attachments may be used interchangeably.

Road improvement work, pipe-line construction or other excavating activities may result in damage or destruction to the cable if its presence is not definitely indicated. Warning signs are accordingly placed on each side of a road under which a cable is laid, at pipe line and railroad crossings and any other locations where excavating work seems probable. Maps showing the cable location are furnished to highway authorities, railroad, and pipe-line companies and others who might

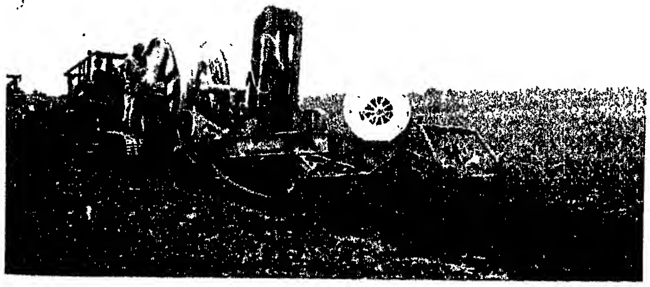

FIG. 6—COMPLETE CABLE LAYING EQUIPMENT

engage in construction or repair work in the vicinity of the cable. The route is also regularly patrolled as an added precaution.

In connection with the splicing, the lead sleeve covering the splice necessary every 750 ft. was at first protected by a cast iron case. When branch or stub cables were required out of the main cable, a modified form of cast iron splice case was used which provided two openings at one end. The splice case was filled with an asphaltum compound to insure protection against soil corrosion for the lead sheath and sleeve, and an asphalt paint was applied to the outer surface of the case.

The cast iron splice covering was found to be rather expensive and it was felt that a cheaper protection

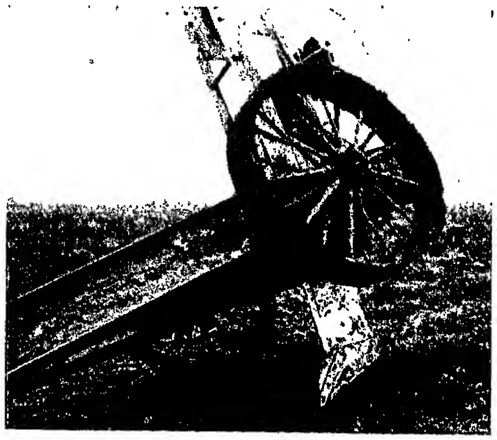

FIG. 7—ROOTER PLOW—IMPROVED DESIGN

would serve equally well. This protection consists of a wood case, made of 2-in. creosoted yellow pine lumber. Space for branch cables is provided by two openings in one of the end pieces. The exposed lead sheath and sleeve within the case are painted with an asphaltum

compound and covered with three layers of muslin tape which is also painted with the compound.

In ordinary underground conduit installations the loading manholes are built of concrete or brick. For tape-armored cables, less expensive manholes are built of 2-in. creosoted yellow pine. Fig. 8 shows one containing a cable and loading coil case but with the cover omitted. Such a manhole costs less than one-third that of the most economically built concrete manhole of

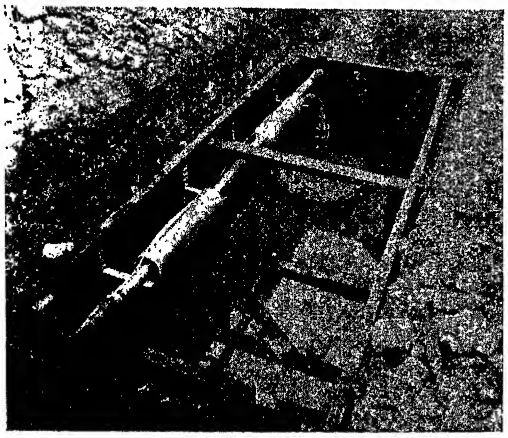

FIG. 8—CREOSOTED WOOD MANHOLE WITH CABLE

similar dimensions. It is usually 12 ft. long, 4 ft. wide, and 3 ft. deep. No floor is provided, the loading pots being buried in the earth as shown. After the top is placed, it is covered with earth, the depth from the surface to the top of the manhole being at least 18 inches. This is necessary as it is desirable not to interfere with the use of the land for ordinary agricultural purposes. Since the manholes and cable are not visible above ground, markers are usually provided at each manhole and at points along the cable route to enable

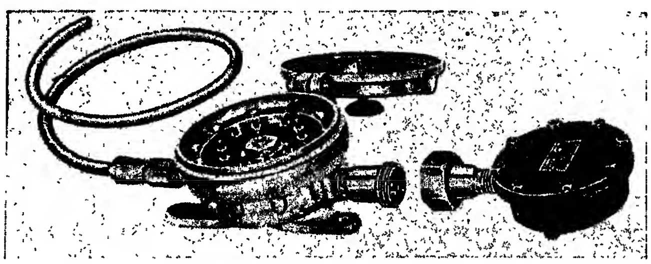

FIG. 9—COMBINED CONTACTOR—TERMINAL

ready location in cases of trouble or the placing of additional loading coils or a future cable. The markers are concrete or wood posts to which are attached plates with manhole numbers, distances and direction to the cable or other pertinent information.

Electrical tests on tape-armored cables do not differ appreciably from those used for unarmored cables. It is estimated that 5,150 individual measurements are made per mile of cable and this is the minimum normal amount required. If conditions difficult of correction are encountered—and these are sometimes found—many of the tests must be repeated. For the cables between St. Louis and Dallas, the estimated minimum number of individual test measurements reaches the rather astonishing total of 4,500,000.

Since the location and clearing of troubles in buried cables is usually more difficult than for those on pole lines or in clay conduit, it is desirable that a tape-armored cable when first placed be as free as possible of defects that would allow moisture to enter it. This end is met by testing the lead sheath with nitrogen, under pressure, at the factory, upon arrival at the destination, just before the cable is laid or plowed in, a day or two later, and then before splicing operations begin. As splicing necessitates removal of sheath at each end of a length of cable, most of the gas is lost. Nitrogen is again introduced on completion of splicing in one loading section, 6,000 ft., and allowed to remain for about two days. If no leaks are found the loading coils are spliced in and the loading splices tested with

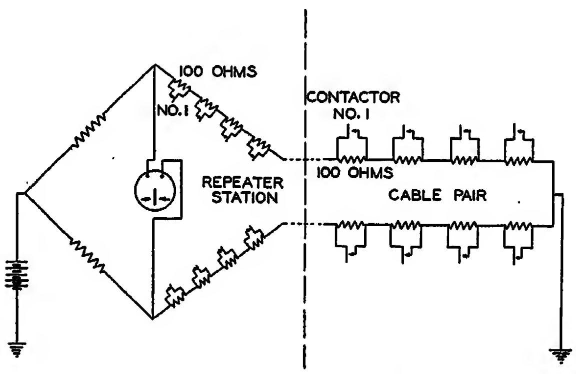

FIG. 10—GAS PRESSURE ALARM CIRCUIT

gas. Gage readings are taken and recorded during all these tests. A more extended discussion of the application of gas-pressure testing for the detection of sheath breaks both during installation and afterward while the cable is in service has been given in a previous paper.[2]

Two recent improvements in connection with constant gas-pressure testing on completed cables seem worthy of mention, however. First is the combined contactor terminal shown in Fig. 9. This outfit can be mounted either in a manhole or on a post. It has the advantage over the separate units of being more compact; the contactor, which is the more delicate of the two, can be replaced very easily and the terminal is made gas tight.

Second is an improved alarm circuit that avoids a difficulty possible in the earlier circuits; namely, that the operation of any one contactor will render the alarm circuit insensitive to the subsequent operation of any

2. *Recent Developments in Telephone Construction Practises*, B. S. Wagner and A. C. Burroway, A. I. E. E. TRANS., July 1929, p. 836.

other contactor in the 50-mile cable section until the first contactor is disconnected or the gas pressure is raised in the cable section it covers. This is due to the fact that a single circuit is used for alarm purposes for an entire repeater section of cable. The plan shown in Fig. 10 avoids this difficulty. The wheatstone bridge principle is used. When the gas pressure lowers, the contactor, say at location No. 1, closes. This short-circuits the 100-ohm resistance at the contactor and unbalances the bridge at the station, causing the alarm there to operate. Resistances equal in value to those at the cable contactors are terminated in jacks at the station and the attendant merely inserts a non-metallic plug in turn in each jack until the correct one is found as evidenced by silencing of the alarm. It will be noted that when the plug is inserted in jack No. 1, a resistance of 100 ohms is added to the circuit. As this is the amount removed by the operation of contactor No. 1, the resistance of the entire circuit is restored to normal and the bridge is automatically rebalanced and remains so until another contactor operates. This system has been tried out and found to operate very satisfactorily.

It is evident that there are times when the gas alarm is inoperative. For example, a large sheath break or repair operations may permit practically all the gas to escape from a plug section. To protect the cable during such periods, another maintenance device known as the low-insulation resistance alarm, is often used.

This system operates when moisture entering the cable lowers the insulation resistance between the conductors and the cable sheath. A number of pairs of conductors in the outer layer, *i. e.*, adjacent to the lead sheath, is connected in the repeater station to a relay mechanism which automatically and in regular sequence, switches these conductors to a sensitive insulation resistance measuring device. A decrease in the resistance below a predetermined value causes an alarm to operate. Wheatstone bridge measurements are then made to locate the trouble and men are dispatched to clear it. Because of the minute currents flowing through the moistened insulation, recourse is had to the vacuum tube by which these exceedingly small currents may be amplified sufficiently to cause the operation of an alarm.

So far nothing has been said as to the costs of tape-armored cables and sufficient experience has not been had with them to develop comprehensive and average data. Each of the cables in the Southwestern Company's territory has been placed under conditions which do not admit of direct comparisons. Soil, rock, topography, the time of year during construction, types of machinery and construction methods with continuous improvements on each job, and many other factors have all operated to make cost comparisons difficult. However, some general conclusions seem possible, based on the limited experience so far obtained by the Southwestern Company.

Using the cost of tape-armored cables as unity the following relations are given:

Type of plant	Costs
One tape-armored cable	1.00
One aerial cable on pole line	0.90
Two tape-armored cables	1.00
Two aerial cables on pole line	0.85

It is apparent that aerial plant costs somewhat less than the buried type. However, certain developments now under consideration promise a rather substantial reduction in the cost of buried cable and if these prove successful, it is quite probable that buried plant may cost even less than aerial cable.

There is another factor difficult of evaluation and that is the effect of service interruptions. Continuous and dependable service is one of the principal objectives of a telephone company and service failures are not only annoying to patrons but result in loss of revenue to the company. It would seem that buried cable should be subject to less damage from external sources than aerial construction, and if further experience bears this out the desirability of more extensive use of buried cables may become apparent.

Discussion

H. R. Fritz: In a recent presentation by Harrison and Silver* well grounded buried tape-armored cable is shown to provide an approximate shielding of 80 per cent against externally induced voltages, relative to the voltages induced on open wire. This shielding is about 30 per cent larger than that obtained from well-grounded lead-covered cable without armoring.

An extended investigation of the possible shielding benefits of tape-armored cable has been made on an actual field installation. The results were in substantial agreement with the figure given above. The effects of other grounded structures in the neighborhood of the test section were also noted, their contribution being to increase the shielding by a few per cent. It was further revealed that additional shielding may be obtained by grounding the pairs in the cable at each end through the balanced points of repeating coil windings. Under favorable conditions shielding in excess of 90 per cent may be anticipated from the combined effects of the steel tape, other grounded structures and wire drainage.

Of the several parameters governing the shielding afforded by any cable sheath the admittance of the sheath to earth is particularly interesting because of the wide variations that might be expected to occur between different localities. Extensive investigation of tape-armored cables in this territory prior to, during and after installation has revealed a rather singular behavior. Since both the sheath and tape are covered with layers of impregnated jute wrapping it might be anticipated that the distributed admittance of sheath and tape to earth would be large. This was found to be true prior to and just after laying the cable. Subsequently the admittance increased very rapidly. Typical measurements indicated leakances of approximately 0.000004 mho per kilofoot initially, which increased to from 0.01 to 0.3 mho per kilofoot within two weeks after laying. In terms of resistance this means a change from 250,000 to as low

Trends in Telephone and Power Practise as Affecting Coordination, by W. H. Harrison and A. E. Silver, A.I.E.E. Trans., June 1931, p. 437.

as 3.3 ohms per kilofoot. The leakance, once acquired, is retained despite subsequent drying.

The cause of this increase has not been determined nor has it been established whether it may not be affected by changes in the manufacturing process or the composition of the wrapping. For the locations where it does take place the result is of course extremely favorable to a full realization of the shielding from the sheath and tape.

Stanley Skinner: From the standpoint of routine maintenance and operation one of the new problems presented by buried cable has to do with the protection of the sheath from mechanical injury and from soil corrosion.

In the buried cable which was placed in service between Kansas City and Joplin in May of this year, there is a total of a little more than eleven acres of lead sheath which must be kept intact. This sheath is about one-eighth inch in thickness and is easily injured. The tape armor is usually effective in preventing sheath damage such as abrasions and punctures which might be inflicted by sharp stones and the like during the installation period or afterward, but it may be punctured by a direct blow from a pick or digging bar. Consequently considerable thought has been given to the question of protecting the cable from accidental damage during road grading operations, strip coal mining, excavations for pipe lines, etc.

The most effective protection is that afforded by care in the selection of the route. It is usually possible to locate the cable on private property at such a distance from roads and buildings that the probability of its being disturbed during road grading operations and by ordinary farm excavations is remote. It is desirable to follow, as nearly as possible, a direct line from repeater station to repeater station and with proper care such deviations from a straight line as are necessary may be made without materially increasing the length of the cable. Through the use of long tangential sections, a cable may be located as much as a mile away from a direct line between two repeater stations without increasing its total length more than a few hundred feet.

Road crossings are unavoidable and some extra precautions are required at such points. The best protection seems to consist in increasing the depth to which the cable is buried and in carrying this increased depth past the property line to a point where the cable will be clear of probable road widening operations. Similarly it is advisable to increase the depth at points where the cable crosses small streams and gulleys. Certain types of soils are subject to very rapid erosion and this makes it necessary to increase the depth of the cable along hillsides or in descending the banks of streams.

Since experience with tape-armored cable is limited actual field results as to the effectiveness of the jute and asphalt covering as a protection from soil corrosion are not available. Laboratory tests have indicated that the asphalt impregnated coverings should very effectively protect the lead sheath under practically all conditions normally encountered. Some situations may, however, be found which would make it desirable to employ additional protective measures. One or two cases have been encountered in the coal fields where the surface water is unusually acid in reaction; in the same vicinity it was also necessary to use wire-armored cable in crossing streams. In these cases the cable was encased in a wood trough filled with asphalt and the trough buried in a trench under the bed of the stream. While it is doubtful that additional protection was actually needed in these cases, the precautions taken are mentioned as illustrative of the many points which must be watched in a job of this nature.

By establishing favorable contacts between the telephone forces and contractors, pipe line companies, highway officials and others an attempt is made to prevent accidental damage to the cable by enlisting the cooperation of the agencies which may be responsible for this damage.

Due to the limited experience with buried plant, maintenance practises are still in the formative stage. In addition to the buried cable between Kansas City and Joplin, there is an underground cable in clay ducts along the highway between Kansas City and St. Louis. This will enable comparisons of the cost for routine maintenance of these two types of toll plant. From present indications it appears that the cost of maintaining the buried cable will not exceed that of unarmored cable in clay conduit.

The Time Factor in Telephone Transmission

BY O. B. BLACKWELL*

Fellow, A. I. E. E.

UNTIL comparatively recent years the telephone engineer gave little attention to transmission time in his problems. For all practical purposes he could assume that speech was transmitted instantly between the ends of telephone circuits. The rapid extension of the distances over which commercial telephony is given and the introduction of long telephone cables has changed the situation and has introduced time problems in telephone transmission which are of large technical interest and difficulty. As a result, time problems are receiving more consideration in the technical papers published in recent years on transmission. The attached bibliography lists a considerable number of such papers. There seems to be no paper, however, giving a general overall picture of this subject. The present paper gives briefly such a picture.

The time factor introduces five different types of problems in telephone transmission:

1. *A Slowing-Down of Telephone Communication.* In talking over long lengths of certain types of cable, the time interval between the formation of a sound by the speaker and its reception by the listener may become of sufficient magnitude to slow down conversation. This is not a serious matter with the types of circuits now used in the United States, even for the longest distances between points in this country. It does, however, become of considerable importance when we consider the joining together of long lengths of cable in this country and long lengths in Europe with possibly long lengths of intervening submarine cable.

2. *Delay Distortion.* Difference in the speed of transmission over a circuit of the different frequencies which make up speech. This may introduce peculiar distortions in speech which cause considerable interference.

3. *Echo Effects.* These arise from the fact that parts of the energy transmitted over a circuit may be reflected back from points of irregularity in it, particularly at the ends. Small amounts of the energy may wander back and forth over a circuit two or more times. While these echoes may affect both the talker and listener, they generally have the greatest effect on the talker who may have an uneasy feeling that the distant party wishes to break in on the conversation.

4. *Effects of Voice-Operated Devices.* To overcome echoes, and under some conditions to hold circuits stable, it has become the practise of connecting into certain types of circuits, relay devices operated by the transmitted speech currents which render inoperative transmission in the opposite direction. In some cases delay in transmission may be an advantage in the operation of such devices. In other cases it may introduce serious difficulties. Conditions may be set up in which it is difficult for one party to interrupt the other. In other cases, portions of conversations may be locked out. If the voice-operated devices are not properly adjusted or if considerable noise is present, the devices may not function properly and speech mutilation may result.

5. *Fading.* In radio, the well-known phenomenon of fading is due to waves arriving at the receiver over different paths, the transmission times of which are such as to cause alternate strengthening and weakening of the received signal by alternate phase agreement and opposition. While this factor is mentioned here for completeness, it will not be discussed further as it is beyond the scope of this paper to discuss the problems introduced when there is more than a single path between the sending and receiving ends of a circuit. The present paper is limited to the conditions which hold where not more than one path is involved in the transmission in each direction.

Speed of Transmission

Before considering these problems in more detail it would be well to define what is meant by the speed of transmission over a circuit. There are several speeds which may have significance according to the problem involved.

Whenever a change in applied voltage is made at one end of a circuit, some evidence of this is transmitted over the circuit to the receiving end at the speed of light. In general, however, except in radio, no sufficient action to be of use is transmitted at this speed and it is largely of theoretical importance.

The speed which the engineer generally has in mind in thinking of line transmission is the speed at which the crests or the troughs of the waves pass along the line when a single-frequency potential is continuously applied at the sending end. This usually is referred to as the speed of phase transmission in the steady state. While this usually approximates the speed in which we are interested, it may in particular cases differ considerably from it. In fact, in certain types of artificial circuits the crests and troughs of the waves travel toward rather than away from the sending end.

This speed may best be explained as follows:

Since the speed of transmission is generally different for different parts of the frequency range, for simplicity, a particular narrow frequency range, say between the frequencies N_1 and N_2 is considered. It is supposed that

*Trans. Development Engr., American Tel. & Tel. Co., New York, N. Y.

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electrical filters are applied to the circuit limiting the frequencies over it to approximately this range. If then, a voltage having a frequency say at midpoint of this narrow range is applied to the circuit for a short interval and then removed, the speed at which the disturbance thus set up travels down the circuit is the speed in which we are interested. A spurt of energy of this type is evidently similar to that which takes place in carrier telegraph systems when a dot impulse is applied to the circuit. This speed can be looked at, therefore, as that of carrier telegraph signals so formed.

The speeds on this basis of a number of standard constructions which represent good engineering practise today are approximately as follows:

Type of circuit	Approximate speed in miles per second
Cable circuits loaded with 88-mh. coils at 3,000-ft. spacing	10,000
Cable circuits loaded with 44-mh. coils at 6,000-ft. spacing	20,000
Cable pairs of non-loaded 16 B. & S. gage	130,000
Non-loaded open-wire pairs	180,000
Radio	186,000

Causes of Time Lag in Transmission

A pair of wires of zero resistance in free space separated from all other conductors and without leakage would transmit electrical waves over it at the speed of light. It will be noted from the above table that non-loaded open wires transmit at a speed not differing widely from this. What retardation exists comes largely from the glass insulators which cause an increase in capacity and the resistance of the wires, which causes an effective increase in inductance.

In cable circuits there is still further retardation by the increase in the capacity between the wires because of the necessity of using a certain amount of solid dielectric and particularly from the increase in the inductance of the wires when loading coils are inserted in them to decrease attenuation.

In actual circuits there is still some further retardation by the apparatus which is necessarily inserted at the terminals and at intermediate points along the circuit. The figures given in the above table are for the bare circuits. The delays caused by apparatus will, in general, reduce these speeds from 10 to 25 per cent.

Slowing-Down of Telephone Conversation

Considering the first of the above factors, it is noted that so long as the speaker at one end of a telephone circuit continues to talk, the listener at the other end will hear the speech in proper time relation, independent of how much absolute delay there is in going from one end of the circuit to the other. However, when the speaker asks a question and waits for the answer, the slowing-down effect on his conversation will evidently be the time of transmission of his question to the distant end and the transmission back from the distant end of the answer. Considering the speed shown in the table, however, consideration may be taken of the fact that the non-loaded constructions, both open wire and cable, and the radio, are of such high speed that conversations could be carried on over them for the longest distance between places in the world without appreciable difficulty. This, however, is not the case for the loaded construction. Assume, for example, that a length of 4,000 miles would cover the wire line distance between any two points in this country. For the slowest construction noted, an interval of 0.8 second is required for transmission to the distant end and return. While it is possible to carry on conversation over a circuit with this delay, it is larger than is considered desirable. The faster of the loaded constructions shown would give a delay over circuits of this length which represents somewhere about the limit of what, at the present time, is considered satisfactory. Incidentally, the slowest of the constructions shown, for this and other reasons, is not proposed for use except for comparatively short distances.

Communication engineers must look forward to the time when the longest cable distances in North America are connected, in some cases by submarine cable, to long lengths of cable in Europe. With this as an ultimate objective, this matter of the direct effect of delay on conversation has become of considerable interest.

An appreciation of the transmission time on long telephone circuits may perhaps be gained by considering the distance required to produce an equivalent delay of sound waves traveling in air. For example, it takes about as long for a radio wave to travel half way around the earth at the equator as it does for a sound wave to travel from one speaker to another when the distance separating them is about 75 ft. Incidentally, the time required for a radio wave to travel from the earth to the planet Mars would be from about 3 to 20 minutes, assuming that it got there at all. Evidently if we have neighbors on Mars we can never hope to carry on conversation with them.

Telephone engineers have devoted considerable attention to the effects of delay on the telephone users in an effort to determine how far the electrical waves should be permitted to travel over different types of circuits. Since the present constructions do not offer any particular difficulties, for the distances now in use, a look into the future has been taken by means of artificial delay circuits. One method has been to loop back and forth loaded conductors in a cable until the desired delay was obtained. Another method has been to record the talkers' waves on a phonograph and pick up the impressions with a second needle, displaced the desired amount from the first so as to introduce delay into the conversation.

Considerable use has also been made of pipes or "acoustic" delay circuits. Fig. 1 shows an illustration of a brass pipe delay circuit used in experimental work. Fig. 2 shows the circuit in schematic form. In addition to the pipe, which is looped back and forth to conserve

space, the circuit involves telephone receivers at the two ends. The one at the sending end converts electrical energy into sound which is transmitted through the pipe and the one at the receiving end converts the sound waves back into electrical energy. The pipes are quite suitable because they have approximately the same delay at all frequencies. Various devices are required to reduce the reflections which occur at the junction of the pipe and the receiver and to equalize the attenuation.

Using devices of this nature, experimenters have found it possible to talk fairly conveniently over circuits representing time intervals as great as 0.7 second in each direction. So great delays would be considered undesirable for commercial use, however. Delays of about a third of this, in general, are considered about the maximum which is satisfactory.

Delay Distortion

In designing circuits which are electrically long, care must be exercised to insure that the transmission times

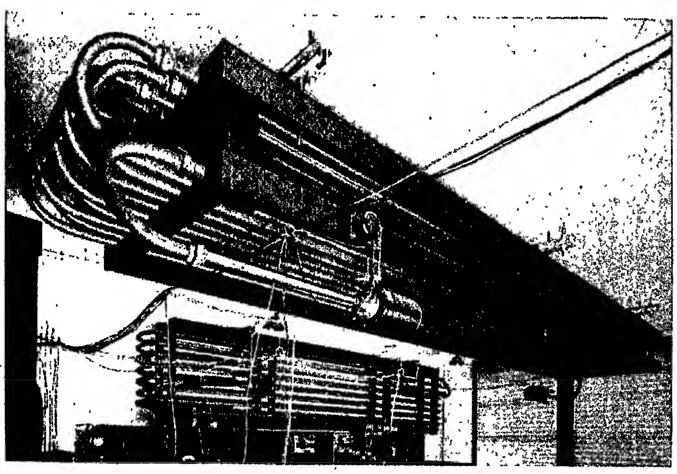

Fig. 1—Acoustic Delay Circuits

for all frequencies in the transmission range are sufficiently alike to avoid objectionable transient phenomena. These effects may occur in one-way circuits as well as in two-way circuits and are not related to echo effects.

The appearance of these transients to the listener depends on whether the excess delay is at low frequencies or at high frequencies. It is rather difficult to describe the characteristic sound of a circuit with low-frequency delay. A high-frequency delay, if it is in an extreme form, sounds as though a high-pitched reed, such as a harmonica reed, was being plucked whenever there is a sudden transition in the voice sounds being transmitted over the circuit.

The characteristic effects of transients are conveniently described by the aid of oscillograms of spurts of alternating current taken before and after being sent over circuits having various delay characteristics. To begin with, it must be recalled that when any wave shape is applied to a circuit, the transmitted wave in the circuit can be expressed as the sum of the series of sinusoidal waves whose frequencies range from very low to very high values.

In the case where a sinusoidal wave of frequency F is suddenly applied to the sending end of the line, the effect may, therefore, be explained as due to an infinity of sinusoidal waves so proportioned and phased as to add up to zero, up to the instant of application of the wave, and to equal the steady-state value of the wave at that instant. Of these waves, the most important

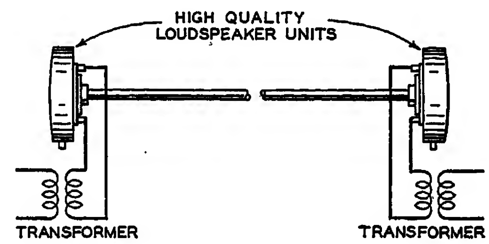

Fig. 2—Acoustical Delay Circuit Showing Two High-Quality Loudspeakers with One Connected to Each End of Tube Forming Delay Circuit

have frequencies close to F. They are propagated over the line individually with the velocity corresponding to the frequency. If the velocity of the line is the same for all frequencies, they will evidently add up to give the same overall wave shape at the receiving end of the line as at the sending end.

If, on the other hand, the velocity is not the same for all frequencies, there will be more or less distortion and transients in establishing the wave, though ultimately the pure wave of frequency F will be established. Several oscillograms will be shown to indicate transient

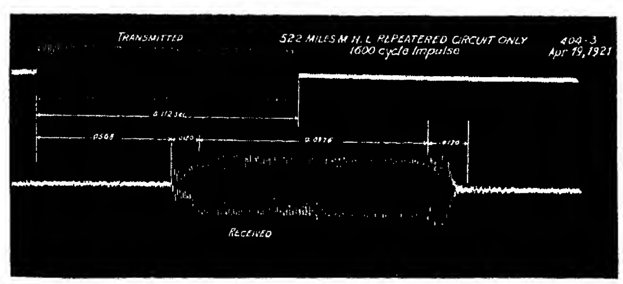

Fig. 3—Transients in Medium Heavy-Loaded Circuit

effects which are experienced under various conditions.

Fig. 3 is an oscillogram showing a spurt of 1,600-cycle current as applied to and received from a loaded circuit having fairly large delays in the upper part of the transmitted range compared to the delay at lower frequencies. Remembering the nature of the oscillations at the beginning and end of the applied spurt, it will be observed that the current at the receiving end consists at first of a fairly low frequency which builds up in frequency and magnitude to the steady-state value. At the end of the spurt the same transient is experienced,

but in this case the higher frequency currents which have been delayed in the line are at the tail end of the train.

Fig. 4 shows a 200-cycle current with many harmonics of higher degree transmitted over a circuit having large delay at low frequencies. It will be noted that these high or harmonic frequencies are received in advance of the 200-cycle wave. This is because the 200-cycle wave

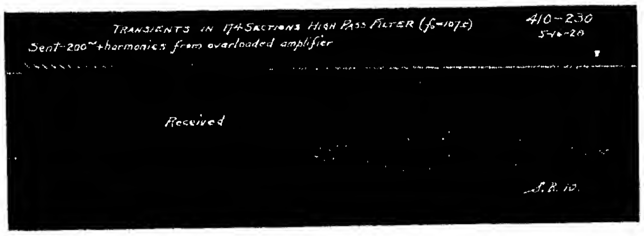

Fig. 4—Transients in High-Pass Filter

is subject to appreciable delay while the higher frequencies are not. This circuit, while actually made up of artificial networks, had characteristics similar to certain types of long cable circuits for the lower part of the telephone frequency range.

Fig. 5 shows transient effects of a 600-mile composited 19-gage H-174 side circuit. The zero lines of the three curves of this figure show slight effects of crosstalk and other interference. These effects are not, however, of sufficient magnitude to interfere with the general appearance of the signals. The upper line shows the applied 1,000-cycle current. The next line shows the current as it was received at the end of the line. The transients which are produced at the beginning and ending of the signals are evident.

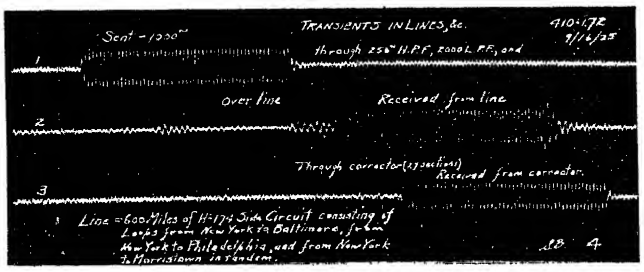

Fig. 5—Correction of Transients in Medium Heavy-Loaded Cable Circuit Through Use of Phase Collector

By the insertion of proper networks it is possible to correct for distortions of this kind. In the last line there is shown the received current when a delay correcting network of this kind is applied in series with the circuit. It should be noted that while the delay in the reception of the signal is somewhat increased (as shown by the displacement of the whole signal further to the right) the transients at the beginning and stopping of the signal are very much reduced.

Echoes

In designing telephone circuits which are electrically long, an important problem is presented by the necessity of avoiding echo effects. These are caused by reflection of electrical energy at points of discontinuity in the circuit and are very similar to echoes of sound waves in an auditorium. The reflected waves are usually considered as echoes when there is an appreciable delay with respect to direct transmission. Some of the reflected waves return to the receiver of the talker's telephone so that if the effects are severe he may hear an echo of his own words. Other reflected waves enter the receiver of the listener's telephone and, if severe, cause the listener to hear an echo following the directly received transmission.

Reflections of voice waves occur in all practical telephone circuits. It is only in telephone circuits of such length as to require a number of repeaters, how-

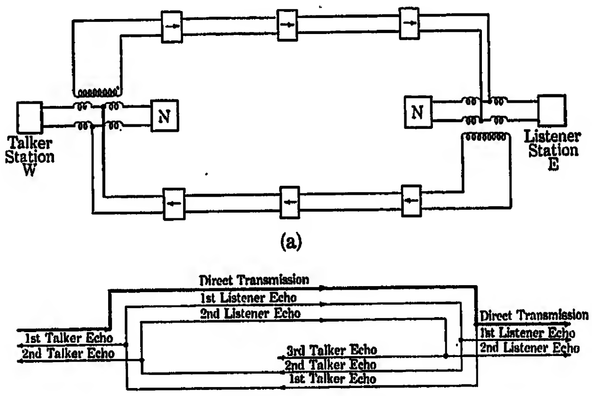

Fig. 6—Four-Wire Circuit

ever, that echo effects become serious. The fact that the circuits are electrically long makes the time lag of the echoes appreciable. At the same time, the telephone repeaters overcome the high attenuation in these long circuits and consequently make the echoes louder. The seriousness of the effect is a function of both the time lag and the volume of the echo relative to the direct transmission, becoming greater when these are increased.

In telephone circuits the most important points of discontinuity are usually the two ends of the circuit. In a four-wire telephone circuit these are the only points of discontinuity.

Fig. 6 shows a schematic diagram of a four-wire telephone circuit and a schematic representation of the direct transmission over the circuit, together with the various talker and listener echoes which are set up. The rectangles at the extreme right and left are intended to represent the telephone sets used by two subscribers at the west and east terminals of the circuit. The rectangles marked *N* represent electrical networks which simulate or balance more or less perfectly the impedance of the telephone sets. In the four-wire circuit the rec-

tangles with arrows represent one-way repeaters or amplifiers. At each terminal the two separate one-way circuits comprising the four-wire circuit are joined together by means of the familiar balanced transformers. When the subscriber at W talks, the transmission passes to E over the upper path in the four-wire circuit. This is indicated by the heavy line labeled "Direct Transmission" in part b of the figure. When subscriber E talks, transmission passes over the lower path in a similar manner.

Considering part b of the figure, it will be noted that when direct transmission is received at the east end of the circuit, a portion of the current passes to the opposite side of the four-wire circuit and is transmitted to the subscriber at the west end as a talker echo. Similarly, a portion of this talker echo is transmitted over the upper part of the circuit to the listener at the east end of the circuit as a listener echo. Successive talker and listener echoes follow this, as indicated in the diagram. If the networks at the two ends of the circuit can be made to simulate accurately the subscriber circuits, none of these echoes will exist. A high degree of simulation, however, is impracticable in an economical telephone plant under usual conditions. In two-wire circuits with many repeaters the echo paths may become very complicated.

An interesting case of "echoes" is that which may be produced when two radio stations are sending out the same program at the same wavelength. The program as received by one of these stations over wire circuits is, of course, slightly delayed with respect to a station nearer the source of the program. It is possible then for a receiving set properly located to receive both of these stations, in which case if the time difference is sufficient one of them will sound like an echo of the other. In this case there may be the added peculiarity that if the weaker station is the one at which the program is received first it will appear that the "echo" is in advance of rather than following the sound which appears to cause it.

Time Effects with Voice-Operated Devices

Switching devices operated by the voice currents themselves are frequently introduced into long telephone circuits. In general, the effect of such devices is to render inoperative transmission in the direction opposite to that of the speech waves which are going over a circuit at the particular instant. The first use of any considerable importance to which such devices were put was in connection with long circuits for the purpose of preventing the building-up of undesirable echoes. More recently, however, long radiotelephone circuits have come into use. These circuits may vary rapidly in transmission effectiveness. If these circuits are arranged to be operative in both directions at a time it would be very difficult to prevent their becoming unstable and possibly setting up oscillations. For this reason such circuits are frequently operated with switching arrangements such that the circuits leading to both transmitting stations are normally disabled and rendered inoperative. When a subscriber speaks at either end, therefore, the voice currents must operate switching devices which restore the circuits leading to his transmitting station. Incidentally, this must render inoperative the receiving circuit at the same time.

A very interesting application of time delay has been made in connection with radio systems so operated. In this arrangement the voice currents when they reach the disabling point are passed through an artificial line in which a desired amount of delay is incorporated. Just before entering this line a fraction of the energy is taken, rectified, and made to operate the switching mechanism for restoring the circuit to operating condition. This switching is so arranged as to be completed by the time that the voice currents have passed through the artificial delay circuit and are ready to proceed down the line. If it were not for this arrangement a small

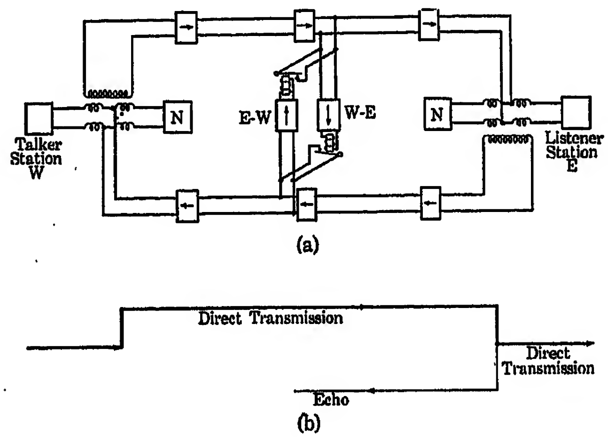

Fig. 7—Four-Wire Circuit with Echo Suppressor

part of the speech currents might be dissipated during the interval while the switching mechanisms were operating.

Fig. 7 is similar to Fig. 6 noted above with the exception that the application is shown of an echo suppressor.

When the subscriber at the left of the drawing begins to talk, the waves set up in his telephone are transmitted over the upper part of the circuit. Upon reaching the input of the echo suppressor, a small part of the energy is diverted to short circuit the lower branch of the circuit, as indicated. Meanwhile, the main transmission passes on to the subscriber at the right. Echoes which return in the lower part of the circuit are blocked as indicated. After the talker has ceased speaking, the device remains operative for a time equal to the delay of the echo as measured from the input of the device to the disabling point plus an additional time to take care of echoes in the circuit between the four-wire terminal and the subscriber.

When the suppressor releases, the circuit is again free to transmit in either direction. When the right-

hand subscriber talks, the action is similar except that the other half of the echo suppressor operates.

In practical use the echo suppressors are so carefully controlled that telephone users are generally unable to tell whether a suppressor is on the circuit or not. This is due to the short delays and careful adjustments of the time function of the device. It is possible, however, if the delays are longer and the adjustments are made with less care, to introduce two types of difficulty. If one subscriber talks fairly steadily he may hold the suppressor operative so continuously that it is difficult for the other party to break in on the conversation if he so desires. If one subscriber started to reply almost simultaneously with the termination of the other's speech, part of his reply might be blocked at the echo suppressor along with the last of the echo.

Further difficulties arise if two circuits, each containing an echo suppressor of this kind, are switched together in tandem. In this case it would be possible if both subscribers started talking simultaneously to block completely each other's speech.

In the case of radio circuits operated as noted above, difficulties are introduced somewhat similar to that of two echo suppressors in tandem.

The above will sufficiently suggest the types of difficulties which arise from delay in connection with voice-operated devices. Certain of the papers in the attached bibliography consider these problems in more detail.

In preparing the attached bibliography, no attempt has been made to make it complete. It is believed, however, to contain most of the important publications on the subject.

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Discussion

A. F. Rose: Referring to the table on page 142, it would appear that the speed of propagation of radio circuits is so high that echo effects would not be important as compared with the usual type of long distance cable circuit. For example, the radio portion of the New York-London circuit which is approximately 3,400 miles in length would require 0.018 second for transmission. This time is so short that the chances for objectionable effects, such as lockout, would be small. However, there is some additional delay in the wire line and as discussed in previous articles on the New York-London circuit, it is necessary to add delay artifically to the circuit in order to permit time for the satisfactory operation of voice actuated devices. The additional delay of these circuits and the wire lines increases the one way transmission time to about 0.09 second in the long wave, and 0.05 second in the short-wave circuits. Voice-operated relays which are necessary to preserve stability, also make the echo characteristics of these circuits satisfactory from the standpoint of overall service results. Some of the above delays account for occasional lockouts. Effects which may be mistaken for lockouts sometimes occur due to relays becoming operated by high noise.

As a matter of interest the approximate delays in various parts of the transatlantic circuits are summarized below.

Wire lines	Seconds
New York-Rocky Point (70 mi. H-44)	0.004
Cupar-London (425 mi. H-89)	0.032
London-Rugby (85 mi. H-89)	0.006
Houlton-Bangor (120-mi. N.L.O.W.)	0.001
Bangor-New York (472 mi. H-44)	0.025
New York-Lawrenceville (50 mi. H-44)	0.003
Netcong-New York (50 mi. H-44)	0.003
Delay circuits	
Transmitting	0.021
Receiving	0.004
Filters, etc., about	0.005

Impulse Voltage Tests on a 4,800-Volt Distribution Substation

BY H. W. COLLINS,* E. E. PIEPHO,* and J. J. TOROK†
Associate, A. I. E. E. Associate, A. I. E. E. Associate, A. I. E. E.

Synopsis.*—Lightning voltage flashovers have been experienced in substations feeding a 4,800-volt ungrounded distribution system. Lines enter the substations through three-phase, underground cables varying in length from a few hundred to about nine hundred feet. Lightning arresters are connected at the substation bus and at the junctions of overhead lines and entrance cables. The arcovers have consistently occurred on lines equipped with voltage regulators and at points between the line terminal of the regulator and the station end of the entrance cable.*

Impulse voltage tests were made on one of the substations which had been taken out of commission, to determine the cause of the flashovers and to find a remedy. Surge voltages from a lightning generator were sent into the station through the entrance cable of a circuit equipped with a voltage regulator and volt-time oscillograms were taken at the principal points of interest.

Oscillograms are presented which show that the impedances of the regulator series windings to surges were high enough to cause reflections of the incident wave and a consequent building up of voltage at the station end of the entrance cable.

It is also shown that the energy drawn from the cable through the regulator series windings is so small for the early part of the wave that the lightning arresters on the bus cannot protect the cable against high-voltage surges which may enter the substation.

Other oscillograms presented indicate that partial protection is provided by the arresters located at the overhead line end of the entrance cable. The effectiveness of this protection becomes greater as the entrance cable is shortened, and as the wave front of the incoming surge is made longer.

It is shown that voltage rises sufficient to break down the entrance cable or cause flashovers at the station end may be prevented by shunting low-voltage arresters across the regulator series winding, or by connecting the usual distribution arresters at the station pothead of the cable. The latter method is more desirable because it insures a lower voltage at the substation end of the cable.

DURING the 1928 lightning season The Detroit Edison Company experienced in five substations a total of six arcovers which were caused by lightning voltages entering the stations by way of a 4,800-volt, ungrounded distribution system. The overhead lines of this system enter the substations through three-conductor, underground cables, and lightning arresters are located at each junction of line to cable and at the substation bus. Some of the distribution lines are equipped with three-phase voltage regulators in the substations. These regulators are *Y*-connected, but the neutral is not brought out and is insulated from ground. Fig. 1 shows the layout of a typical distribution line with a regulator.

Besides being unusually large in number for a single season, the arcovers were of unexpected severity. In each case the lightning voltage causing flashover entered the substation by way of a distribution line on which there was a voltage regulator. Furthermore, the flashovers occurred at some point between the substation pothead and the "line" side regulator terminals, and their nature indicated that they were caused by voltages in excess of the breakdown voltages of the cable pole and bus lightning arresters which inspection showed to be in good operating condition. This consistency in the location of the flashovers indicated that the impedance of the regulator series winding to surges was probably great enough to cause reflections of surges entering the substation, and so result in the building up of a voltage at the regulator "line" terminals high enough to cause flashovers. Tests were conducted jointly by the Westinghouse Electric and Manufacturing Company and The Detroit Edison Company in an effort to determine the cause of the flashovers and find a remedy. These tests were made in Detroit on Elmdale Substation which had been taken out of commission and was being dismantled.

Description of Equipment

Elmdale Substation. This 4,800-volt distribution substation was of the open pipe-frame construction, and

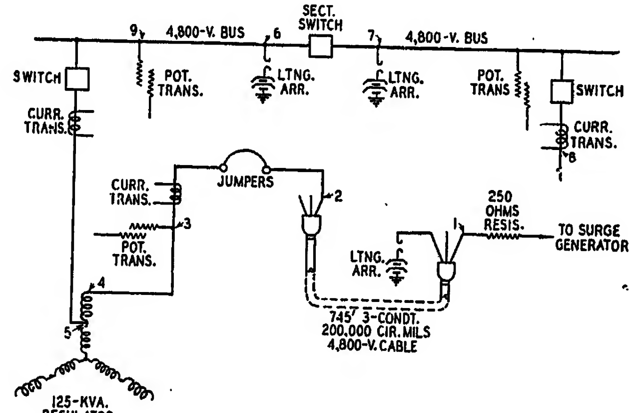

FIG. 1—TYPICAL LAYOUT OF A CIRCUIT IN ELMSDALE SUBSTATION WITH SPECIAL REFERENCE TO THE APPARATUS TESTED WITH SURGE VOLTAGES

the bus copper and all leads were insulated with varnished cambric. One distribution line with voltage regulator was left in the substation, and its 745-ft. entrance cable was looped back so that both ends were in the station. This cable was a three-conductor, 200,000 cir. mils, lead-covered cable insulated with

*Detroit Edison Company, Detroit, Michigan.

†Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

Presented at the South West District Meeting of the A. I. E. E., Kansas City, Mo., October 22-24, 1931.

oil-impregnated paper 5/32 in. thick on the conductors with a 5/32 in. overall belt. A dead, 24,000-volt, three-conductor cable line 8,900 ft. long terminated in the station and was available during the tests.

Lightning Generator. The impulse voltages used during the various tests were obtained from the Westinghouse Electric and Manufacturing Company's 1,000,000-volt lightning generator and auxiliary equipment.[1] Since only 180,000 volts were required in the tests, the generator was reconnected to deliver this voltage with a capacity of 0.075 μf.

Cathode-Ray Oscillographs. Two portable cathode-ray oscillographs were used during the tests, one being an improved Norinder oscillograph,[2] and the other a George oscillograph of the hot cathode type.[3] A concentrating coil was added to the latter to assist in focusing the beam. The apparatus in the measuring system included a resistance potentiometer and a delay cable.

Connections of Equipment

The substation apparatus tested is shown in Fig. 1. The pothead position (1) on this diagram, was taken to represent the cable pole pothead of the entrance cable. It was to this pothead that the surge generator was connected by a resistance, and through it the voltage surges entered the station. It will be noted that the three phases were joined electrically by potential transformers which were connected open delta, and by the voltage regulator which was Y-connected with neutral ungrounded. Each phase had a lightning arrester at the cable pole pothead (1) and at a point on each bus section (6) and (7); and various combinations of these arresters were tried during the tests. The arresters were rated 6,000 volts for use on an ungrounded system. Suitable lightning arresters were also available for connection at the substation pothead, and for shunting the regulator series winding.

Determination of Resistance to Simulate Line Conditions

An analysis of a traveling surge entering the cable from the overhead line shows that, due to the lower surge impedance of the cable, the wave on the line will be reflected with reduced magnitude and reversed polarity. The voltage of the surge entering the cable will be less and the current greater than in the original line surge. The following equations show these effects:

$$e = \frac{2\,Z_c}{Z_c \text{ plus } Z_L} E_L$$

$$i = \frac{e}{Z_c} \text{ where}$$

e = voltage of surge in cable
Z_c = surge impedance of cable
Z_L = surge impedance of line
E_L = voltage of surge on line
i = surge current in cable

1. For references see Bibliography.

If the surge generator should be discharged directly into the cable, the current drawn by the arresters would be excessive due to successive reflections of current. Since it was not possible to apply the surge to the cable by means of an overhead line, a resistance was placed in series with the surge generator to limit the

Fig. 2

current in the cable to a value which would approximate that of a surge entering from an overhead line. The following equation gives the surge in the cable in terms of the surge generator voltage, E, and the series resistance, R.

$$e = \frac{Z_c}{Z_c \text{ plus } R} E$$

In order to simulate a surge entering from an overhead line

$$\frac{Z_c}{Z_c \text{ plus } R} E = \frac{2\,Z_c}{Z_c \text{ plus } Z_L} E_L$$

$$R = \frac{Z_L \text{ plus } Z_c}{2} - Z_c$$

Substituting the usual value of Z_L (500 ohms) and

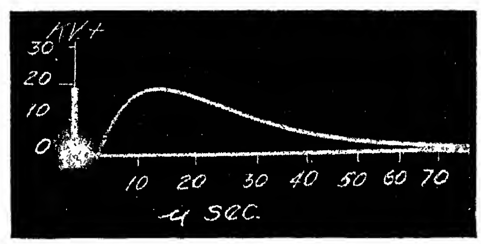

Fig. 3

Z_c (40 ohms) in the above equation gives 230 ohms for R. In the tests a series resistance of about 250 ohms was used.

Test Procedure

Two general types of impulse voltage waves were used in the tests. One wave, shown in Fig. 2 had a voltage rise from zero to maximum in approximately one microsecond at its front. The other wave, Fig. 3 which was secured by connecting 1,360 millihenrys inductance in series with the surge generator, had a wave front with voltage rise to maximum in about

ten microseconds. These two different surges were used in the tests to determine generally what effect the steepness of wave front would have upon the reflection of the impulse at the voltage regulator. A very steep front wave, as nearly rectangular as possible, was required to show reflections clearly on the oscillograms. Tests with surges having slower wave fronts more nearly like natural lightning were also desirable in order to gain information more nearly representative of actual lightning conditions.

Various combinations of the lightning arresters shown in Fig. 1 were tried during the tests, as well as other combinations made by adding arresters at the station pothead (2) and by shunting low-voltage arresters across the regulator series winding.

Tests were first made with resistances of various magnitudes connected to the bus to simulate the effects of other circuits connected to the bus. Oscillograms showed that the surge voltage appearing on the bus decreased as the connected resistances were decreased, but that the shapes of the impulse voltage waves impressed at the cable-pole pothead (1) and the station

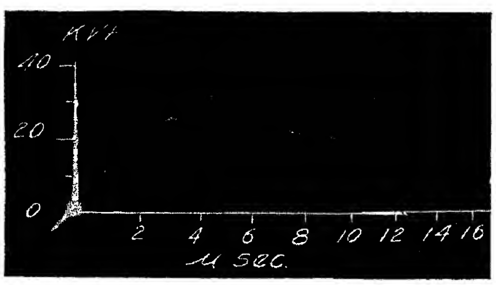

Fig. 4

pothead (2) were unaffected. Most of the tests were therefore made with the station bus open-circuited.

When the two phases which were not connected to the surge generator were grounded at the cable-pole pothead (1) to simulate connection to an overhead line, the oscillograms did not differ from those taken with these phases open-circuited. Consequently, most of the tests were made with the latter arrangement.

In other tests, surges were applied at position (8) Fig. 1, and oscillograms were taken at cardinal points, but the bus lightning arresters limited the impulse voltages to a safe value at all points. Consequently, no further tests of this type were attempted.

During the early part of the testing, volt-time oscillograms were taken at positions (1), (2), (3), (5), (6) and (8), but the effects of the instrument transformers were so slight that the oscillograms taken at positions (2) and (3) were identical, and those taken at positions (5), (6) and (8) were alike. It was therefore decided to make measurements only at positions (1), (2) and (5). The oscillograms taken at these three points are quite different because of the cable-pole lightning arresters, the cable itself and the voltage regulator.

Since all the surges were sent through only one phase, the voltages induced on the other phases are of interest. These two phases have magnetic and capacity coupling with the surged phase, to which they are also connected through the regulator and the potential transformers. These windings, however, have high impedances and it is chiefly by their capacity effect that any surge energy is transmitted through them. Oscillograms were at first taken on the two idle phases concurrently with those taken on the phase connected to the surge generator, but when it became evident that the voltages in-

Fig. 5

duced on them were not serious in magnitude (usually about one-fourth the voltage on the surged phase) further measurements on them were omitted.

Test Results

Effect of the Regular Series Winding. The impulse voltage tests indicated definitely that the energy drawn from the cable through the series winding of the regulator by the lightning arresters and other equipment connected to the bus was very small, especially for the first part of the wave. The high impedance of the regulator series winding is well shown by comparison of the oscillograms taken at the cable-pole pothead (Fig. 4), at the station pothead (Fig. 5) and at the bus

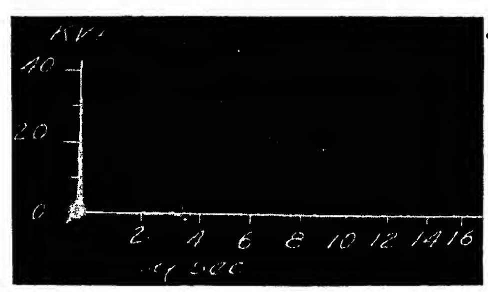

Fig. 6

(Fig. 6). Fig. 4 shows a surge of about 25-kv. crest entering the cable, and Fig. 5 shows that this wave was increased to a crest value of about 43 kv. by the partial reflection at the voltage regulator. The positive, reflected wave returned to the cable-pole end where it caused sufficient voltage rise to break down the lightning arresters located there. These arresters prevented further voltage rise and returned a negative, reflected wave to the station end of the cable, which reduced the voltage at that point to about 23 kv. Fig. 6 shows

how much slower the rise of surge voltage is on the bus than at the station pothead, due to the high impedance of the regulator series winding.

Using the slow front wave, oscillograms were taken at the cable-pole pothead (Fig. 7), at the station pothead (Fig. 8) and at the bus (Fig. 9). The reflections

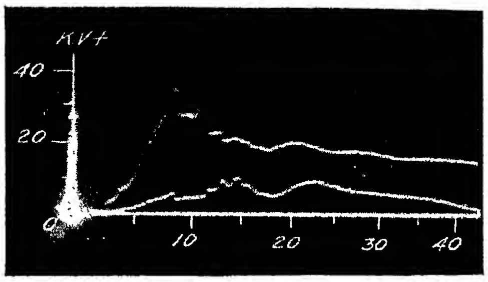

Fig. 7

at the regulator do not show as distinctly as for the steep front wave since the entering wave does not reach its maximum at the cable-pole pothead before the reflection is beginning to return from the regulator and is adding to the voltage of the entering wave. If the

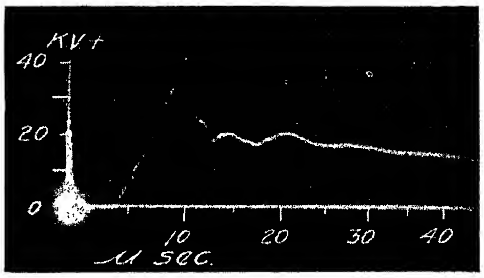

Fig. 8

entrance cable had been long enough so that it would have taken an impulse about 10 microseconds to travel forth and back through it, then the reflections would have been just as distinct as for the one microsecond front surge. Comparison of Fig. 7 and Fig. 8 will show

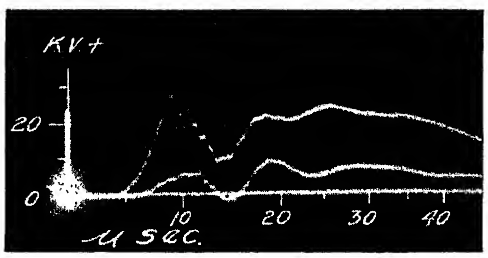

Fig. 9

that the surge voltage at the regulator rises to a greater maximum value than at the cable-pole pothead. Consequently, although the magnitude of the reflections at the regulator is obscured because the reflections occur on the front of the wave, it is evident that they are appreciable. The slower rise of voltage on the bus shown in Fig. 9 also indicates that the regulator series winding offers considerable impedance even to the slow front wave which was used.

The slow passage of energy through the regulator series winding is further illustrated by the oscillograms taken at the station pothead (Fig. 10) and at the bus

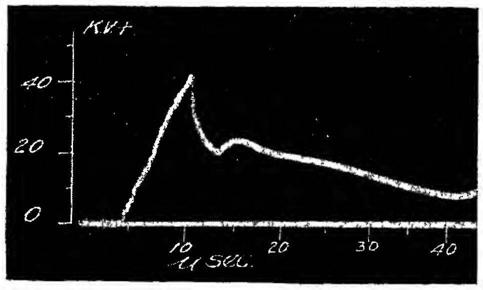

Fig. 10

(Fig. 11) with the dead 24,000-volt cable line connected to the bus.

In order to determine if the lightning arresters on the bus provided protection for the cable, the lightning arresters at the cable pole were disconnected. When

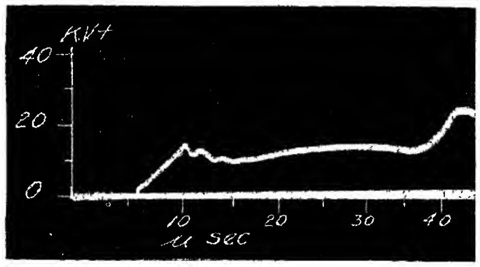

Fig. 11

a voltage surge was discharged at the cable-pole pothead into the cable for this condition, the regulator impedance remained very high for a long enough period

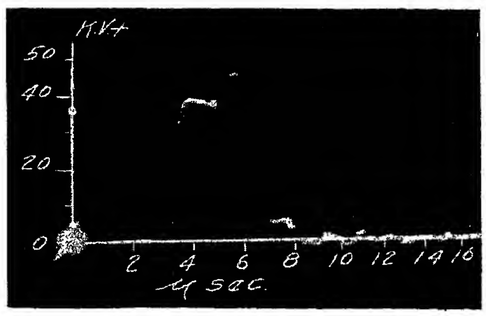

Fig. 12

to cause a flashover at the station pothead. This is shown in the oscillogram Fig. 12, taken at the station pothead for practically the same impulse voltage as was used when Fig. 5 was taken. It is therefore evident that the regulator series winding makes the lightning arresters on the bus ineffectual in preventing voltage

rise in the cable sufficient to cause breakdown of the cable or flashover at some point between the station pothead and regulator when high-impulse voltages enter the station through the cable.

Action of the Lightning Arresters at the Cable-Pole End of the Entrance Cable. The surge-generator voltage was of such magnitude that the crest value of the impulse entering the cable was less than the breakdown voltage of the lightning arresters at the cable-pole end of the

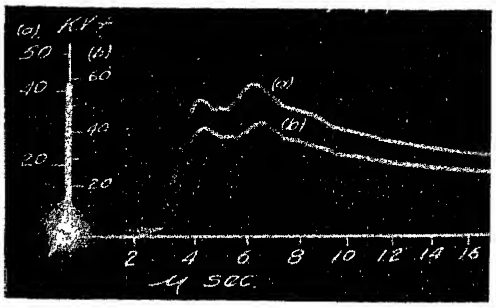

Fig. 13

entrance cable. However, when the positive, reflected wave arrived from the substation end of the cable, the voltage on these lightning arresters was suddenly increased and the arresters operated to lower the voltage. This is shown in Fig. 4 and Fig. 5. Operation of the arresters causes a negative reflection of the impulse sent back from the regulator. When this negative reflection arrives at the regulator it causes a sudden drop of potential at that point.

The time elapsing before the cable-pole arresters relieve the condition of overvoltage at the station end of the cable depends upon the length of the cable, since it is equal to the time required for the reflected wave to travel from the regulator to the cable-pole pothead and back again. This time is about two microseconds for the average length of entrance cable. For such an average case if the wave front of the impulse is greater than two microseconds, crest value will not reach the regulator before the negative reflection from the cable-pole lightning arrester arrives and the voltage at the regulator will not build up as high as for a steep front wave.

Effect of Low-Voltage Lightning Arresters Shunting the Regulator Series Winding. The voltage at the station pothead may be limited to a safe value by shunting low-voltage arresters across it, thus permitting the bus arresters to help lower the voltage at this point. The oscillogram of Fig. 12 was taken at the station pothead with arresters on the bus only, and the flashover shows the lack of protection. When the regulator series windings were shunted by low-voltage arresters, flashover was prevented by the operation of these arresters in series with the bus arresters. This is shown in oscillogram Fig. 13, curve (*a*) having been taken on the bus, and curve (*b*) at the station pothead.

Effect of Lightning Arresters at the Substation End of the Entrance Cable. When lightning arresters were connected at the station pothead, the voltage rise was definitely limited there to the breakdown voltage of the arresters. The flashover in Fig. 12 resulted at the station pothead when the cable-pole arresters were disconnected. This flashover was prevented, as shown in Fig. 14, by connecting lightning arresters at the station pothead. Furthermore, by comparison of curve *b*, Fig. 13 which was taken at the station pothead with low-voltage arresters shunting the regulator series windings, with Fig. 14 it is evident that lightning arresters connected at the station pothead limit the voltage there to a somewhat lower value.

Conclusions

The impulse voltage tests performed on the substation described indicate that:

1. When the surge reaches the regulator, it is reflected by an amount depending upon the surge impedance of the regulator, which in turn depends upon the rate of voltage rise at the wave front and upon the electrical characteristics of the regulator. This reflection adds to the oncoming wave and may cause a rise of voltage at the substation pothead to a value somewhere between 100 per cent and 200 per cent of the wave traveling toward the regulator. The magnitude of this voltage and interval of time it exists at the regulator will depend upon the steepness of the wave front and upon the length of the entrance cable.

2. Because the surge impedances of the regulator series windings remain at high values long enough for a flashover to occur, the bus lightning arresters cannot protect the cable against voltage surges which may enter the substation through it. The lightning arresters at the cable-pole end of the entrance cable limit the voltage there, but they can limit only partially the rise of voltage at the substation end of the cable. If the front of the incident wave is short and the entrance cable is long, approximately double the voltage at the cable-pole end will be impressed at the station end for an appreciable time before the cable-pole arresters relieve this condition.

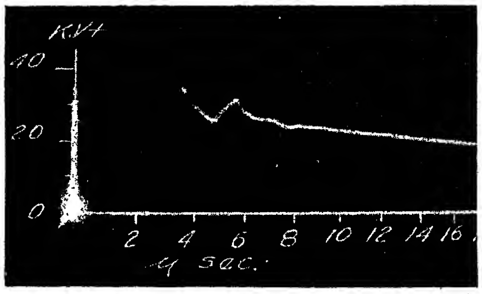

Fig. 14

3. Low-voltage lightning arresters shunted across the regulator series windings operate in series with the bus arresters and limit the rise of voltage on the line side of the regulator to the sum of the breakdown voltages of these two sets of arresters.

4. Lightning arresters at the substation end of the cable limit the voltage on the pothead and the regulator; and, acting in combination with the cable pole and the bus arresters, they will limit the voltage in the cable to the drops across the arresters.

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Discussion

K. B. McEachron: It is interesting to note how the results obtained by Messrs. Collins, Piepho and Torok check those to be expected, based on theoretical considerations and field tests* which have already been published. Late in the summer of 1929 field tests were made jointly with the Consumers Power Company and the Detroit Edison Company in which various combinations of overhead line and cable were studied, with and without lightning arresters. The last conclusion of that investigation agrees closely with the findings of the present authors. It reads: "The increase in voltage at the other end of the cable from the arrester location was about 15 kv. This increase depends upon the steepness of the wave and the length of the cable and may be estimated for any specific case."

With the voltage limited by arresters at the junction of the overhead line and cable, the voltage at the station end will be dependent on how the reflections add at that end of the cable. If connected to a high impedance as the series coil of a regulator or a reactor the voltage may become double that at the arrester if the wave front of the wave in the cable is steep enough so that a wave of reduction traveling back from the arrester fails to reach the station end of the cable in time to reduce its voltage.

The natural conclusion is therefore to apply an arrester at the station end of the cable or at the cable end of the regulator if a considerable distance exists between the end of the cable and the terminals of the regulator. This arrester is applied largely for the purpose of protecting the regulator and other apparatus between the regulator and cable.

The arrester at the junction of the overhead line and cable is for the purpose of protecting the pothead and also preventing interruption to service as the pothead frequency represents the weakest point in the line insulation. The arrester ground should be connected to the cable sheath for the best results as this eliminates the effect of arrester ground resistance.

On page 150 the authors state that "Tests with surges having slower wave fronts more nearly like natural lightning were also desirable" etc. It seems to me that to be consistent with the studies on high-voltage circuits that waves much faster than those used by the authors are likely to occur. Since the slower waves are less dangerous because the reflections at the station end of the cable are not important it seems that the steepest waves which can occur are the most important. Rates of rise as fast as 1,000 kv. per microsecond have been measured on transmission lines and such a rate of rise would correspond to 20 kv. in 0.02 microseconds which is much faster than any wave shown in the paper. Such short times are difficult from the oscillograph standpoint but their reflections can be calculated. Such a wave would mean practically complete reflection at the station end of the cable if it terminated in a high surge impedance. Since the fast front used by the authors was sufficient to show the reflection, but little would be gained by faster fronts in view of the technical difficulties involved in providing and measuring them. However, it appears very likely that they do occur in practise and must be considered.

D. W. Roper submitted a discussion calling attention to the fact that the Chicago substations were entirely free from the troubles which caused the investigation in Detroit. This discussion was withdrawn because Mr. Roper's paper on *Studies in Lightning Protection on 4,000-Volt Circuits—III*, presented at the Winter Convention, 1932, and printed elsewhere in this issue, explains the immunity of the Chicago stations from such troubles and refers to the paper by Messrs. Collins, Piepho and Torok.

*Study of Effect of Short Lengths of Cable on Traveling Waves, K. B. McEachron, J. G. Hemstreet and H. P. Seelye, A.I.E.E. TRANS., Vol. 49, 1930, p. 1433.

Corona Energy Loss

Influence of Surface Conditions as Affecting Corona Energy Loss From High-Voltage Transmission Lines

BY WM. D. WEIDLEIN*

Associate, A. I. E E.

Synopsis.—Coatings of various materials, lacquers, oils, oxides or paints were applied to conductors of number 2 B & S gage 257.3 mils diameter, solid aluminum or copper conductors. Measurements of corona energy losses above and below critical corona voltages were made by means of a wattmeter setting and water resistor multiplier.

INTRODUCTION

DURING the spring of 1930, corona loss measurements on a 220-kv., 60-cycle, three-phase experimental line, 700 ft. in length and of various sizes (0.91 in. to 1 in. in diameter) and types of conductors were made at the Ryan Laboratory, Stanford University. In connection with these measurements some of the test specimens were cleaned with gasoline and then washed, resulting in at least a temporary reduction of corona loss. The question of a permanent reduction of corona loss and of the influence of surface conditions presented itself.

The following report is on research as suggested by this precise work which was undertaken to determine what variation of corona loss results under various conditions of the surface of a conductor.

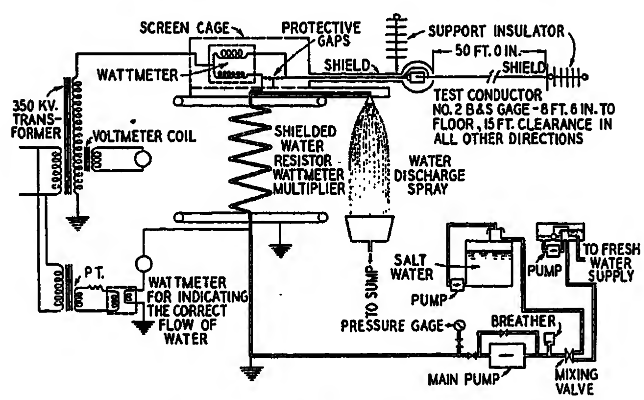

FIG. 1—DIAGRAM OF COMPLETE SET UP OF TESTING EQUIPMENT

EQUIPMENT

The complete set of the test specimens and of the wattmeter setting as diagramatically shown in Fig. 1 is similar to the set-up of a single-phase wattmeter during the tests as noted in the introduction.

The test specimen consisted of 50-ft. lengths of No. 2 B & S gage solid copper or aluminum conductors, supported with 8 ft. 6 in. clearance to ground. The sag at the center of wire was less than 2 in. in all cases. Clearance in all other directions was greater than 15 ft. As to diameters of specimens, when coated, increase in size by 0.001 in. was the maximum, which would produce but very little variation of corona losses.

Insulator loss on the out end is included in all results but is of negligible amount; and for comparison of results this insulator loss does not enter, being present in all tests. Insulator loss of wattmeter end of specimen is completely shielded from wattmeter reading.

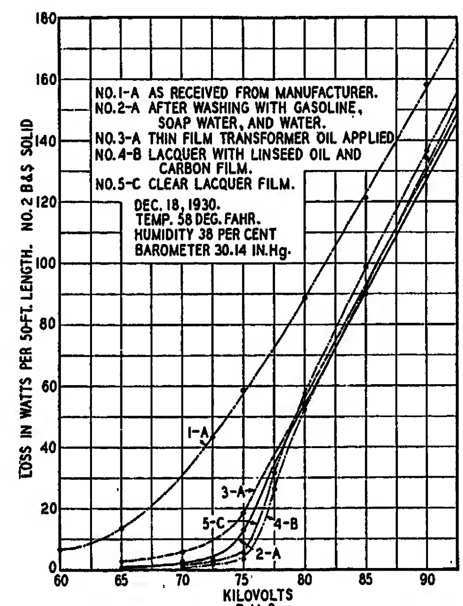

FIG. 2—TESTS ON COPPER SPECIMENS

All tests were made within the laboratory and under as near similar conditions of temperature, humidity, and barometric pressure as possible. Variation of these factors during tests would in no case cause errors that would be appreciable. All results were plotted as read, no corrections being made for such variations. The extreme range of barometric variation was 0.16 in. Hg.

TESTS

The procedure followed in applying voltage was to build up the voltage to 100 kv., reading the loss at this

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*Engineer, Black & Veatch, Kansas City, Mo.

Presented at the South West District Meeting, Kansas City, Mo., Oct. 22-24, 1931.

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point and then at lower values of potential, with 5-kv. or 2.5-kv. intervals, depending upon the rate of change in loss.

The accompanying illustrations are presented as

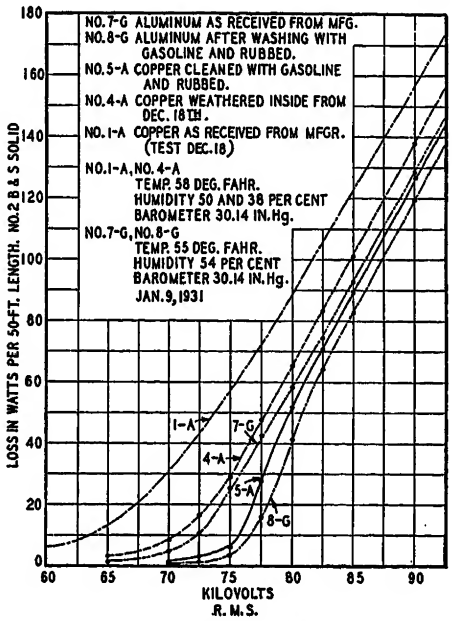

FIG. 3—COMPARISON OF ALUMINUM AND COPPER LOSSES

showing the variation of corona loss with change in surface structure of conductor or application of thin films.

Results of tests on copper specimens are given in Fig. 2. The shape and shift of the curves between

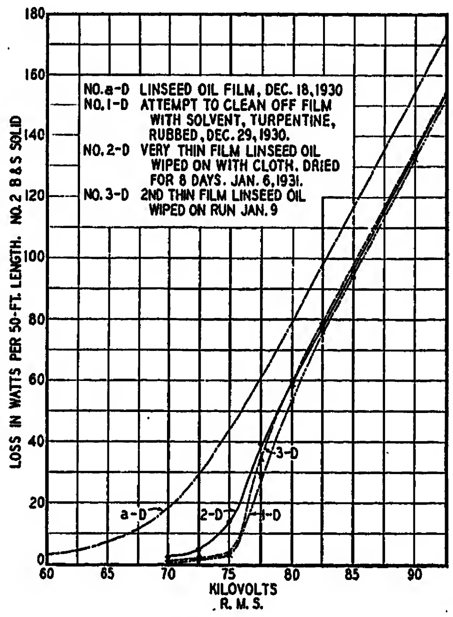

FIG. 4—ILLUSTRATING THE EFFECT OF THICK FILM OF LINSEED OIL

values of 72.5 to 80 kv. should be noted. Joffe's theory that the resistance of a polarized layer decreases when the e. m. f., produced by polarization due to space charge exceeds 2,000 volts, is a very plausible explanation of this action. The high loss from copper conductor as received from the manufacturer is no doubt due to residue left from "pickling" process or from drawing during manufacturing.

A comparison of losses from aluminum and copper conductors is shown in Fig. 3.

In Fig. 4 the first run No. a-D was of a conductor coated with a thick film of linseed oil, brushed on and dried. This wire was then cleaned and a cloth soaked with linseed oil was wiped once along the wire. A complete film was not formed, accounting for the weathering and higher losses after drying. Curve 3-D gives the loss after wiping a second film onto the wire, resulting in a decrease of losses near 75 kv. applied. Apparently there may be some justification for the act that with complete covering with a thin film ionizing velocities of electrons cannot be attained within the film, having insufficient ionizing potential fall; then space charge

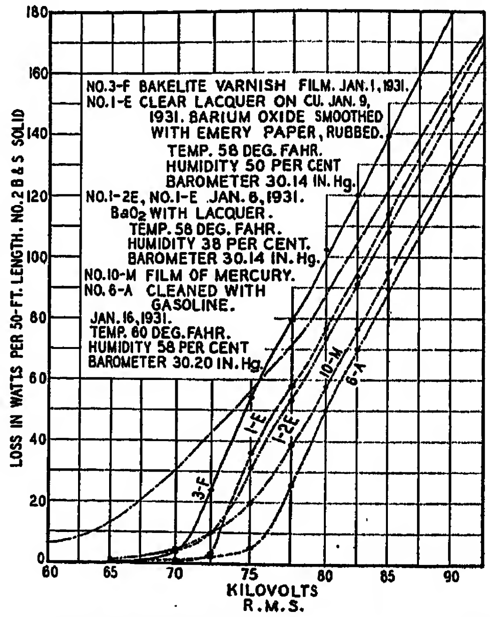

FIG. 5—ILLUSTRATING THE EFFECT OF VARIOUS THIN FILMS

increases to a point where leakage resistance of the space charge starts to decrease, permitting of greater potential fall throughout the adjacent air causing a sharper rise in corona loss.

The curves in Fig. 5 illustrate the effect of various thin coatings of materials. The same type of film was applied to copper and aluminum as shown in Fig. 6.

In Fig. 7 copper and aluminum conductors, previously cleaned and then suspended open to weather, show equal losses over the range tested.

Curve 3-F of Fig. 8 is of a test on a copper conductor coated with a smooth surface of copper oxide formed by heating. With corona forming around this wire at 21 kv., there were no steamers formed over the range of voltage tested up to 150 kv., r. m. s. The corona formation appears similar to that forming around a small wire. With this type of discharge there was very little if any ozone smell detected, which was a decided contrast to a discharge with steamers.

Curves 1-N, 2-N and 3-N show the losses from a conductor heated in acetylene gas. On removal from the gas a granular deposit of carbon covered the conductor, and the losses were as plotted curve 1-N. With

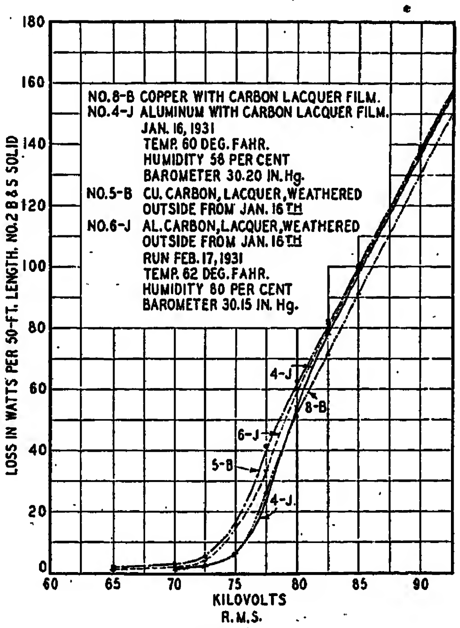

Fig. 6—Comparison of Films on Copper and Aluminum

this carbon rubbed off with a cloth the loss was as plotted in curve 2-N; the interesting point in this connection was that carbon had been deposited to a depth of 1/16 in. into the conductor.

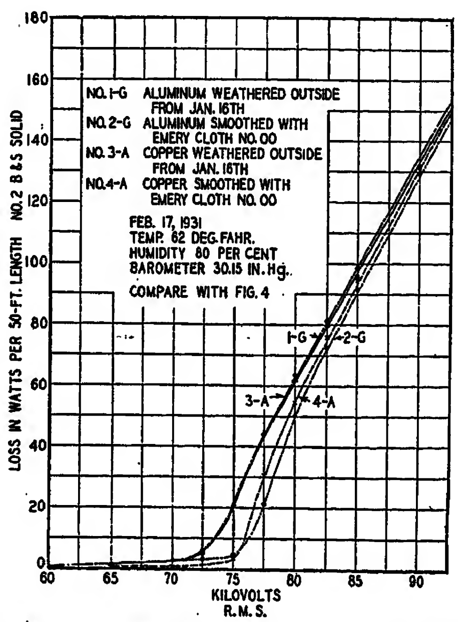

Fig. 7—Clean Aluminum and Copper Conductors Show Equal Losses in Open Air

Conclusion

Thin film coatings of certain materials are effective in decreasing corona loss from high-voltage conductors, whereas thicker films will increase such loss. Such a film may be the polished surface of a metal itself, or the formation of a film by materials that flow readily and solidify with a glaze or a crystalline surface.

Corona losses from copper and aluminum conductors are of equal value after weathering, providing any detrimental effects remaining from drawing have been eliminated.

Favorable results in the reduction of corona loss are illustrated by the shape and shift in position of the curves in several cases. Deviation of the curves to the right from a straight line from high to low values of loss and at voltages of 72.5 to 80 kilovolts for this size of conductor are shown in several tests in support of this conclusion.

Acknowledgment

The author expresses his appreciation and indebtedness to Doctor J. S. Carroll, Doctor Harris J. Ryan and Doctor J. W. McBain for their active cooperation and very helpful advice and suggestions.

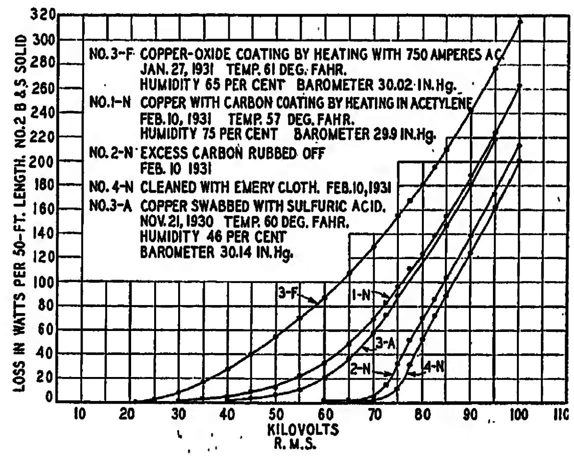

Fig. 8—Test of Copper Conductor under Various Surface Treatments

The copper conductors were furnished by the Anaconda Wire and Cable Company; the aluminum conductors by the Aluminum Company of America, San Francisco office; and the Lacquers and Pigments by the J. W. Fuller Paint Company, San Francisco.

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The Expulsion Fuse

BY J. SLEPIAN* and C. L. DENAULT*
Fellow, A. I. E. E. Associate, A. I. E. E.

Synopsis.—The general theory of extinction of a-c. arcs is reviewed. The expulsion fuse is stated to depend upon the gas blast produced by rapid decomposition of fuse tube material under the heat of the arc. Comparison of interrupting capacities of a soapstone fuse tube and a fiber fuse tube supports this view.

The effectiveness of the gas blast is stated to be due to the high degree of turbulence it introduces into the confined arc space. The theory of the action of such turbulence is discussed.

Data are given as to the composition and volume of gas ejected from a fiber fuse tube.

The voltage interrupting capacity vs. ampere characteristics as obtained experimentally, are given for a fiber tube, and a boric acid lined tube. The curves for boric acid lie much higher than for fiber. The characteristics were found to depen dvery materially on the number of half cycles of arcing. Reasons are given for the shape of the characteristics, and their dependence on length of arcing time.

Data are given showing the effect of variation in size and shape of the tube section. The design problem is discussed of obtaining sufficiently large voltage interrupting capacity at smaller currents without the development of excessive pressures or unmanageably large volumes of flame at large currents.

The use of flame suppressors for deionizing the issuing flame is mentioned. It is shown how, by introducing means for condensing the water vapor, the boric acid lined tube may be completely closed without the development of excessive pressures.

The necessary insulating properties of the gas generating materials used in expulsion fuses are discussed.

I. Introduction

THE expulsion fuse is an extremely simple device quite extensively used for interrupting a-c. circuits of moderate voltage and power. It consists usually of a straight tube open at one or both ends, made of fiber in which the fusible current carrying element rests. In spite of its apparent simplicity and widespread use, the principles upon which it functions are not at all generally understood. Engineers seem to have been satisfied with extremely loose and inadequate descriptions of the process by which, in it, the arc is caused to be extinguished. For example, a text book on circuit interrupting devices gives as the *modus operandi* "the sudden expansion of the air inside the tube when the fuse blows causes the vaporized metal to be blown out of the end of the tube and thus suppresses the arc." But metal vapor is not necessary for the maintenance of an arc, as engineers learn when long arcs short-circuit their lines upon flashover, and it is difficult to see what would cause the precise synchronization of the sudden expansion of the air with a current zero which is the moment at which the arc is actually extinguished.

The very name "expulsion fuse" itself is a loose description which fosters erroneous thinking in suggesting that the arc is "expelled" from the tube, to perish due to lack of contact with the terminals of the sustaining circuit. Much flame is ejected from the tube prior to current zero, but this does not mean that the arc is expelled for the arc continues to reside in the tube up to that point since large current is continuing to flow there, and even though flame may continue to leave the tube after the last current zero, the arc is not expelled then because the arc no longer exists after that moment. The tube space is withstanding high voltage with the passage of only very small current. The actual extinction of the arc, that is, the transformation of the space between the electrodes from the conducting state, in which it carries considerable current with moderate voltage, to the insulating state in which it withstands full circuit voltage with only very small current, takes place at current zero within an extremely short interval of time, of the order of 10 microseconds. In so short a time, with even the most extreme assumption as to the magnitude of the velocities, the gases within the tube can move only a small fraction of a centimeter and the proportion of the tube which is voided or scavenged is negligible. In the expulsion fuse the arc is not expelled but exists in such a condition that at a moment of current zero the change from the conducting state to the insulating state takes place with extremely great rapidity.

It seems worth while then to consider more carefully the manner of operation of expulsion fuses so that their application may be better understood and their potentialities further developed.

II. Extinction of A-C. Arcs

It is well to begin with a very brief review of the general principles of the extinction of a-c. arcs. A gas space carrying an arc is conducting because it is ionized; that is, because a considerable number of the normally electrically neutralized molecules are broken up into electrically charged parts called ions. If the arc is to be extinguished, that is, if the gas is to recover its normal insulating state, these ions must disappear. If the ionized gas is left to itself, the ions disappear spontaneously by direct recombination. But this manner of disappearance is relatively so slow as to be of little use in practical a-c. circuit interruption, except for very small powers. In circuit interrupters generally, means are introduced for greatly speeding up the rate of disappearance of the ions.

*Research Laboratories, Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

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To keep a gas space conducting or ionized against the normal recombination or accelerated deionization as occurs in circuit interrupters, the continued activity of certain ionizing agents is necessary. In the electric arc, the combination of electric gradient along the arc and current density in the arc is a very effective producer of ions, and is the only ionizing agent of any consequence in arcs occurring in switching devices generally. While current is flowing, the arc will take such voltage as will cause ions to be produced at a sufficient rate to compensate for the deionization and keep the current going. In an a-c. arc at the instant of current zero, the ionizing activity momentarily ceases but the deionizing activity continues unabated. At such a moment the gas space is recovering insulating properties very rapidly. The voltage necessary to carry the arc into the next half cycle is then much larger than that required by the arc just before the closing of the preceding half cycle, but the external circuit is able to supply this larger voltage of reversed sign to the arc space only after a lapse of time depending on the transient characteristics of the circuit. For practical circuits this time lag is from 10 to 1,000 microseconds. In this time, the arc space may lose its ionization to such an extent that even full circuit voltage is unable to start the arc in the next half cycle. In this case the arc is extinguished. If, however, the deionization has not proceeded far enough, the arc is reignited. Thus extinction of the arc depends upon relative speed of deionization at current zero and the speed of application of reversed voltage to the terminals of the arc by the external circuit.[1]

A very effective means for increasing the rate of deionization is to bring surfaces of solids close to the arc so that ions may collect on these surfaces and recombine there.[2] Thus it is advantageous in circuit interrupters to enclose the arc in chambers or chutes of relatively small dimensions. It is found, however, that there is a great difference in the effect of these surfaces, depending on whether the surfaces are refractory, or whether under the heat of the arc, the surfaces are decomposed giving off large quantities of gas. In the latter case, under proper conditions much higher voltage and higher powered circuits can be interrupted with arcs of given dimensions than in the former case. This increased effectiveness of decomposing walls is believed to be due to the rapid evolution of gas; and the turbulence introduced into the confined arc by the rapid intermixing of freshly generated un-ionized gas is believed to be an extremely effective means for causing rapid deionization at current zero.[2]

III. Theory of Gas Blast Circuit Interruption Device

For the purposes of this paper, it is enough to know that when an a-c. arc plays in a confined space subject to an intense gas blast, then at each current zero it is in a state where it recovers dielectric strength with exceedingly great rapidity. This may, if preferred, be accepted by the reader as an empirical fact without inquiring further into the details of how this comes about. It is interesting, however, to speculate as to what is the detailed mechanism by which the rapid deionization at current zero takes place.

The authors believe that most important in accounting for the effect of the gas blast is the high degree of turbulence it introduces into the bounded gas space prior to current zero. In fact, some experiments by T. E. Browne, not yet published, in which turbulent motion was produced by suitably disposed magnetic fields and without the introduction of fresh gas, showed a rate of recovery of dielectric strength at current zero exceeding many times that obtained without the turbulent motion. Furthermore, the turbulence prior to current zero is important as well as the turbulence during the extinction period itself. This latter is so short, 10 microseconds, that the amount of deionization due to the actual motion of the gas, carrying ions to the bounding surfaces to be discharged in that time, must be negligible in accounting for the dielectric strength recovered in the very short extinction period.

The great turbulence prior to current zero carries volumes of the gas to the bounding surfaces where they are deionized and thrown violently back into the arc space. The un-ionized, freshly generated gas at decomposing surfaces is also thrown violently into the arc path. Thus, the arc section cannot be continuous with a uniform distribution of ionization, but must consist of small volumes of highly ionized gas in close proximity to un-ionized or slightly ionized volumes of gas.

The arc may be thought of as broken up by the turbulence into a mass of fine threads swirling about in the tumultous motion. These threads are highly ionized and are carrying most of the current and are themselves the regions in which ions are being produced. During the motion threads become broken and cease carrying current, and new threads form as older threads split or as the impressed voltage breaks down new paths through momentarily favorable lining up of highly ionized volumes. Of course under these conditions the arc voltage is much higher than it would be if the turbulence did not exist, but the important thing is what goes on at current zero.

Prior to current zero the highly ionized threads are losing ions rapidly by diffusion into the surrounding un-ionized gas, but the current in the threads and the voltage gradient along them causes ions to be generated in them at as great a rate. At current zero the deionization by diffusion out of the threads continues undiminished, but the production of ions stops. Hence the highly ionized threads disappear almost at once and there is substituted for them a very low density of ionization nearly uniformly distributed over the arc space. A very low density ionization requires a high

1. For references see Bibliography.

electric gradient for the production of new ions and thus is explained the rapid recovery by the gas space of the ability to withstand volts with the passage of little current.

IV. The Expulsion Fuse is a Gas Blast Device

Regardless of the details of the theory, we may regard it as empirically established that the expulsion fuse is a gas blast interruption device in which the gas blast arises from the rapid decomposition of the walls of the fuse chamber under the heat of the arc.[2] This may be seen by comparing the arc voltage and the circuit voltage per inch interrupted by an a-c. arc in a tube of relatively refractory material and in a tube of material which is more readily decomposed into a gas. Such a comparison has been made before, and Figs. 1 and 2 give more complete information. Fig. 1 gives data for tests on the circuit voltage interrupting capacity of a 5/8-in. diameter soapstone tube. The numbers next to the points give the number of half cycles of arcing preceding the extinction of the arc. Their significance is discussed in more detail in section VI; they suggest here that the soapstone is not a completely gas-free material, but that under the influence of the arc, a small amount of gas, probably water vapor, is given off. In Fig. 2, the curve for soapstone is compared with that for fiber, this latter curve being taken from Fig. 6. Data and curves for the arc voltage for the soapstone and fiber tubes are also given in Fig. 2. The tests were made in laboratory circuits, air core reactors being used for limiting the current, when the transformers were not directly short-circuited, so that the circuits were highly reactive with a transition period of the order of 10 microseconds.

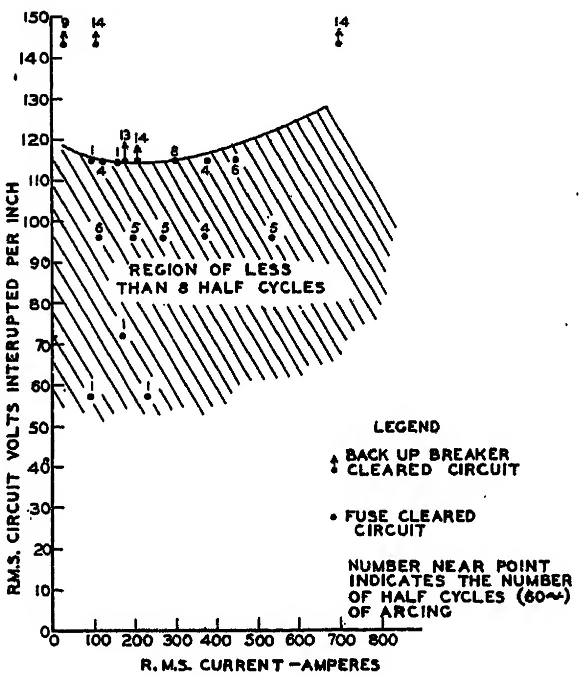

Fig. 1—Soapstone Fuse Tube 5/8 In. Internal Diameter by 4 In. Long

It is noticed that the circuit voltage interrupting capacity and arc voltage for the fiber tube are much higher than for the relatively more refractory soapstone tube.

V. Composition and Volume of Gas in Expulsion Fuse

The material most commonly used for expulsion fuse tubes is horn fiber. Under the direction of the authors,

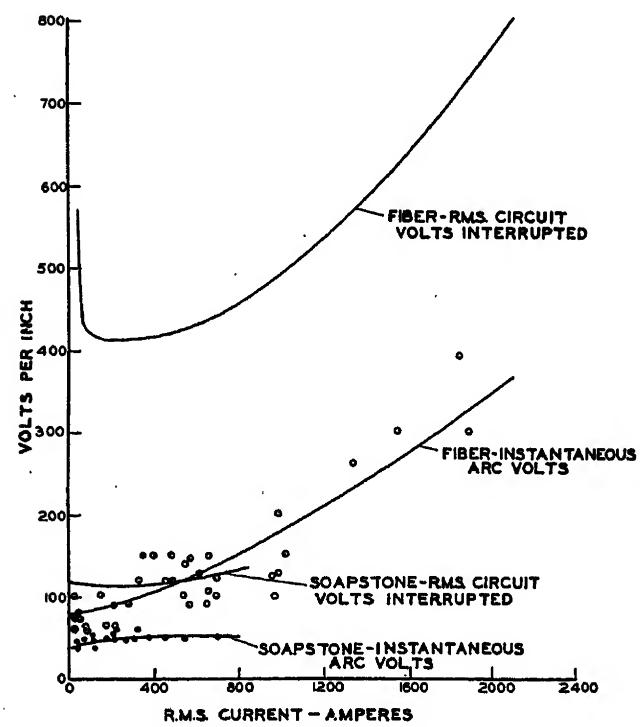

Fig. 2—Soapstone and Fiber Fuse Tubes 5/8 In. Internal Diameter by 4 In. Long

Mr. H. H. Evinger collected the gases coming from a fiber tube in which an arc was playing, to determine their composition and volume. The composition was as follows:

	Test A	Test B
H_2	41%	48%
CO	50	50
Hydrocarbons	9	2

The water vapor given off escaped collection because it condensed and was not drawn off. Since the fiber contains some 10 per cent of water by weight, it may be assumed that in addition to the above gases there was also about 10 per cent of water by weight.

The volume of gas generated as a function of current for a ¾-in. fiber tube is shown in Fig. 3. The volume is reduced to normal atmosphere conditions. While passing through the tube the volume of gas will be multiplied by 5 to 10 due to the elevated temperature and will be divided by a large factor due to the elevated

pressure. Here again the water given off escaped detection because of its condensation.

Materials other than fiber may be used as gas generating materials in expulsion fuses. A material of great promise is boric acid, which may be pressed into solid shapes suitable for lining arc chambers of circuit interrupting devices.[3] The gas given off by boric acid under heat is practically entirely water vapor. The

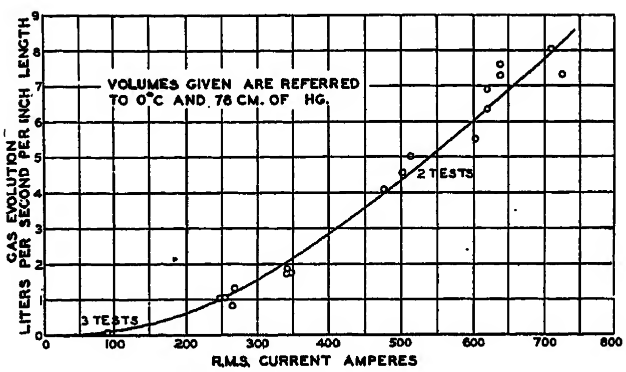

Fig. 3—Gas Produced by the Heat from An Arc 6 In. Long Inside of a 3/4-In. Diameter Vulcanized-Fiber Tube

authors have also experimented with other organic materials giving off gases similar to those from the fiber and with inorganic materials giving off water, carbon dioxide, and sulfur dioxide. Linings of sulfur giving off sulfur vapor have also been used.

VI. Cycles of Arcing-Interruption Volt-Ampere Characteristic

The study of the characteristics of expulsion fuses is complicated by the fact that for moderate currents the voltage interrupting capacity of the arc is not developed immediately, but increases very considerably over a number of cycles from the moment when the arc starts. This property is to be expected from the manner of generation of the gas. For small currents, considerable time must elapse before the surface of the tube exposed to the arc is raised to a temperature at which rapid decomposition takes place. Even after the surface is at the requisite temperature, the material below the surface will still be at a low temperature and the steep temperature gradient in the material will carry heat away from the surface and lessen the rate of decomposition there. After a time the heat will soak into the material, the temperature gradient will be lessened, and the proportion of heat carried away by thermal conductivity will decrease, leaving a greater proportion of heat available for decomposition of the surface. Thus with constant watts input of energy, the rate of gas generation may be expected to increase with time.

The authors have attempted to calculate the influence of this temperature transient upon the gas generation in a fiber tube, using the thermal conductivity taken from tables for fiber, and the specific heat of dry cellulose as a material similar to fiber. With such values for the thermal constants, the time effect should have disappeared before the end of the first half cycle for much smaller currents than experiment shows to be the case. However, the considerable latent heat absorbed by the material due to chemical changes below the temperature for *rapid* decomposition was not taken into account, and as this will be equivalent to multiplying the specific heat by a large factor, the thermal explanation may still be regarded as valid.

It would be expected from this that any means used for reducing the thermal conductivity perpendicular to the surface of the gas forming material would shorten the duration of the thermal transient and lessen the number of cycles of arcing to interrupt a given circuit. The following experiment bears out this expectation. A 40-ampere arc in a 5/8 in. diameter tube, 4 in. long was found to require 9 half cycles before it was extinguished in a 60-cycle circuit of 2,300 volts. A loose spiral of a couple of layers of 0.001 in. paper was placed in the tube and allowed to expand so that it was in loose contact with the tube wall. It was then found that the arc required only 3 half cycles to interrupt the circuit.

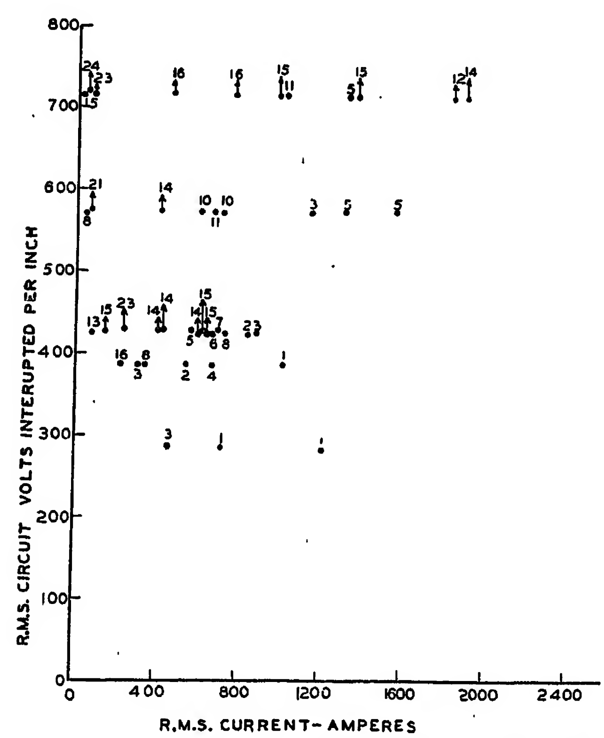

Fig. 4—Fiber Fuse Data. Fuse Tube 5/8 In. Internal Diameter by 4 In. Long

Another factor which undoubtedly plays a large part in causing the time delay in the development of the full interrupting capacity was suggested by T. E. Browne and is that for small currents it will take considerable time before the air originally filling the tube is replaced by the gases formed by the decomposition of the gas forming material, which may have greater voltage interrupting capacity. The nature of the gas used in a blast has a great influence upon the voltage interrupting

capacity of an a-c. arc subjected to the blast. Hydrogen is particularly effective.[5] Unpublished experiments of Browne show that water vapor is also very effective while nitrogen is much less effective than other gases. Study of the data of Fig. 3 shows that the time for displacement of the original air in the tube may be several half cycles for the smaller currents. For very large currents a single half cycle would be long enough

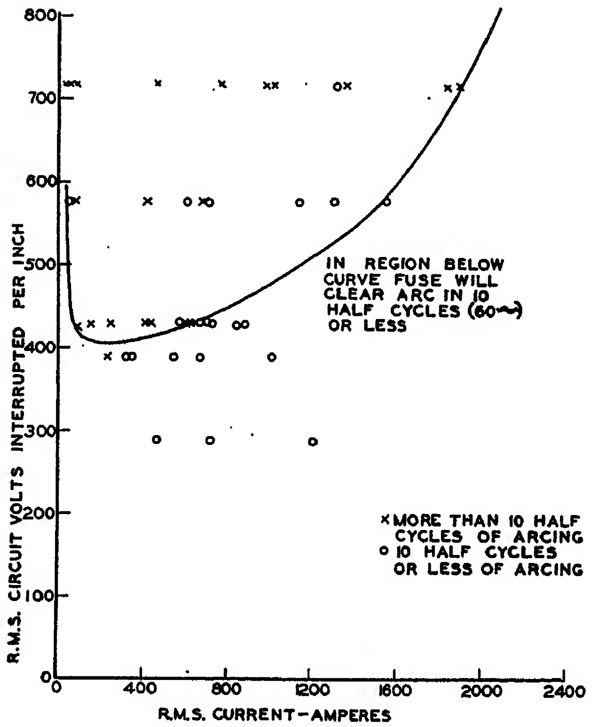

FIG. 5—FIBER FUSE. CIRCUIT VOLTS INTERRUPTED *vs.* AMPERE CURVE FOR 10 HALF CYCLES

for the air in the tube to be completely replaced and for the walls to heat up to such an extent that practically all the heat which reaches the walls will go to decomposing material. The gas blast would then be just as intense at the end of the first half cycle as at the end of the second or third. Hence the voltage interrupting capacity would be no greater at the end of the second or third half cycle than at the end of the first.

For extremely small currents the gas evolution will become so small that it can play no part in the circuit interruption. The voltage interrupting capacity will therefore be the same as for an arc in the open and again it will be the same for the second, third, or later current zero as for the first. But for intermediate currents the voltage interrupting capacity would be expected to be greater at the second current zero than for the first and greater at the third current zero than the second and so on. Thus it will be necessary to show a family of characteristics, each member of the family corresponding to a different number of half cycles of arcing. The different curves should be expected to coincide for large currents and for very small currents, but should be different for intermediate currents.

Concerning the individual curves, because of the rapid rise in intensity of the gas blast with current as shown in Fig. 3, we should expect large voltage interrupting capacity to be developed by large current arcs. Also on general principles a large voltage interrupting capacity would be expected for sufficiently small current arcs.[2] The individual circuit voltage interrupting capacity *vs.* ampere curves should show a minimum at intermediate currents and rise to large values for very small and for very large currents.

In determining the characteristics experimentally the usual inconsistencies met with in such work due to variation in uncontrolled factors are encountered. The inconsistencies in the tests carried out were principally due to variations in the point of the generated voltage wave at which the circuit was closed and at which the fuse blew starting the arc, and to variations in the state of the fuse tube surface due to previous history and relative atmospheric humidity. The individual curves sought are boundaries between regions

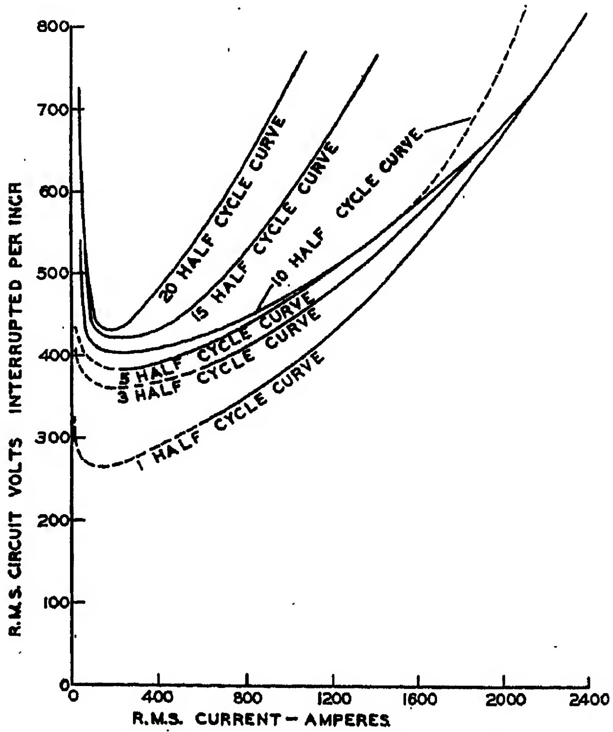

FIG. 6—FIBER FUSE. CIRCUIT VOLTS INTERRUPTED *vs.* AMPERE CURVES

where circuit interruption occurred in a certain number of half cycles and regions where the circuit interruption occurred in a large number of half cycles. Since it is practical to obtain only a limited amount of data such boundaries could be determined only very approximately.

Fig. 4 shows the data obtained for a 5/8-in. diameter fiber tube. The circuits used were again 60 cycle reactive, with transient periods of the order of 10 microseconds. The numbers next to the points give the

number of half cycles to arc extinction. For those points marked with an arrow pointing upward the backing up breaker interrupted the circuit; the number next to them gives the number of half cycles of arcing up to the point at which the backing up breaker opened.

To obtain the characteristic for a given number of half cycles of arcing, those points of Fig. 4 which represent that number of half cycles of arcing or less were marked with circles and those points which represented more half cycles were marked with crosses. Then with the best judgment of the authors a curve was drawn separating the region of the circles from the region of the crosses. A certain amount of inconsistency in the position of the circles and crosses was permitted in the neighborhood of the region boundary for reasons mentioned above. Fig. 5 shows the curve obtained in this way separating the region of circuit interruption in 10 half cycles or less from the region of more than 10 half cycles of arcing.

A number of curves was drawn in this way corre-

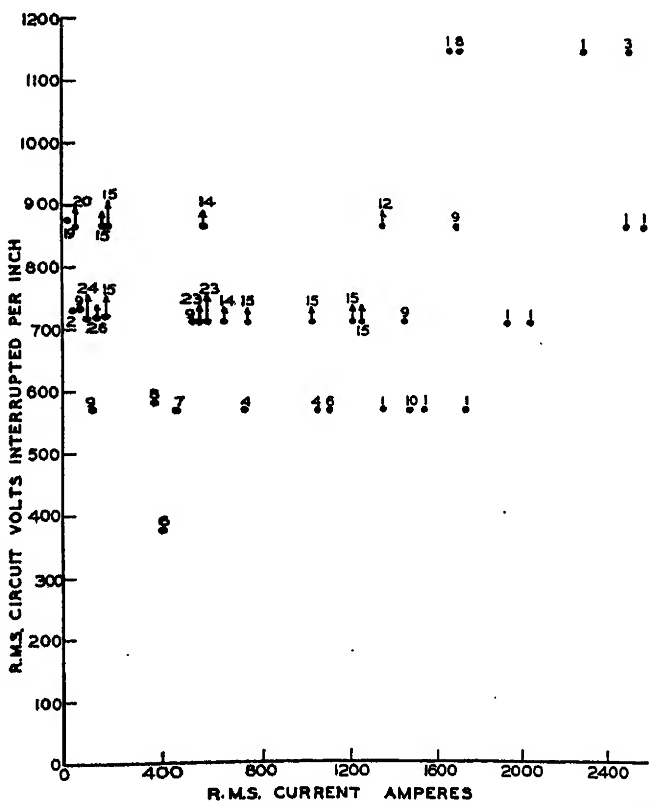

FIG. 7—BORIC ACID FUSE DATA. FUSE TUBE 5/8 IN. DIAMETER BY 4 IN. LONG

sponding to different numbers of half cycles of arcing and then superposed on the same sheet. The curves were then moved about so as to make them consistent with each other and consistent with the ideas expressed above as to the relations of the characteristics with each other. This could be done up to ten half cycles of arcing without any serious violation of the data as is seen in Fig. 6, but the curves for 15 and 20 half cycles seemed to detach themselves quite definitely from the lower number half cycle curves even for the larger currents.

This suggests that for 15 half cycles and more there is a new factor coming in which again increases the rate of gas evolution. This may be due to some kind of mechanical disintegration of the surface beginning at this point. In 15 half cycles the heat will have pene-

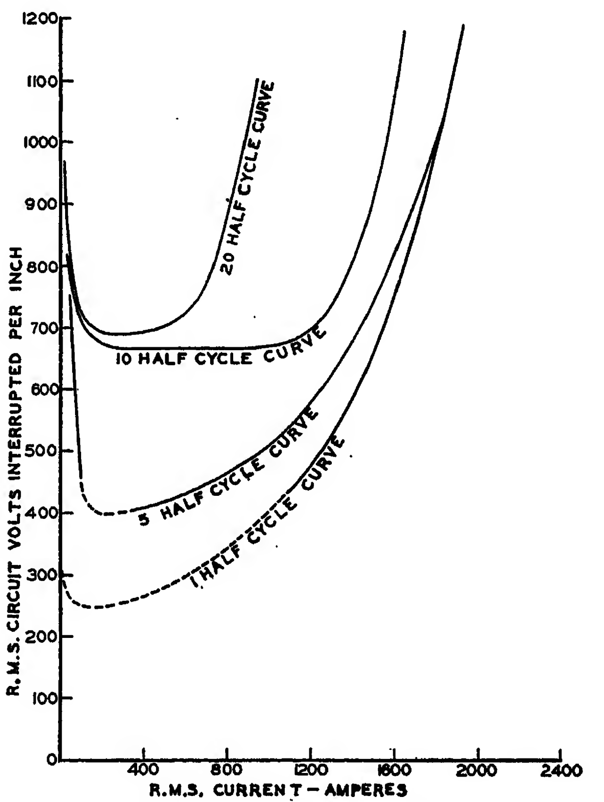

FIG. 8—BORIC ACID FUSE. CIRCUIT VOLTS INTERRUPTED *vs.* AMPERE CURVES

trated several thousandths of an inch within the material. Decomposition will take place even below the surface and the high pressure of the confined gas will cause blistering and loosening or even complete detachment of pieces of the fiber. Such loose or detached pieces of fiber will decompose at an accelerated rate, and thus the gas blast will be increased.

In Fig. 6, the parts of the curves drawn dotted are surmised, and do not have supporting data in Fig. 4.

Data were also obtained and are shown in Fig. 7 for a tube lined with boric acid having 5/8 in. internal diameter. The circuit voltage interrupting capacity *vs.* ampere curves are shown in Fig. 8. These curves lie much higher than those for fiber.

VII. INFLUENCE OF TUBE SECTION SIZE AND SHAPE

From the discussion already given it is quite clear what influence change in size of tube section should have upon the circuit voltage interrupting capacity *vs.* ampere characteristic. With a given rate of gas generation the turbulence and deionization will be far

more intense in a small section tube than in one of larger section. Hence for a given current the arc voltage will be much larger in a small tube than in a large one, but with the larger arc voltage, the energy input will be greater and therefore more gas will be generated for a given current in a small tube than in a large one. This will still further intensify the turbulence and deionization. Hence the circuit volts which can be interrupted will go up very rapidly as the tube size is decreased. Experimental results are shown in Fig. 9.

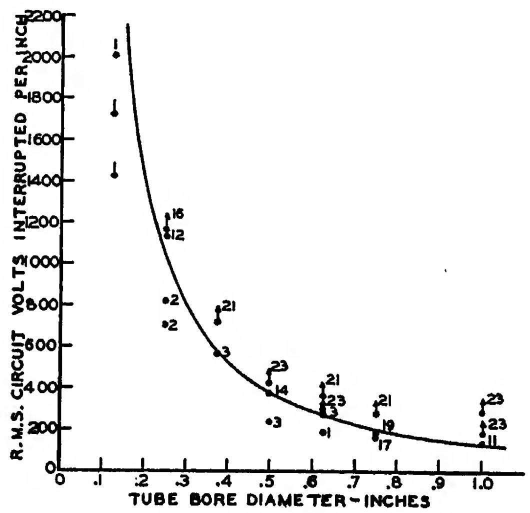

FIG. 9—FIBER EXPULSION FUSE. EFFECT OF VARYING TUBE DIAMETER ON THE CIRCUIT VOLTS INTERRUPTED AT A CONSTANT CURRENT OF 450 AMPERES

The influence of change in shape of tube section may also be anticipated from theory. Comparing a circular section with a narrow rectangular section of the same area it is seen that in the latter all parts of the arc are close to gas generating surface while in the former the center of the arc is more remote from gas generating surface. It should be expected then that the turbulence will penetrate more thoroughly throughout the arc in the latter than in the former and that the circuit voltage interrupting capacity will be larger for the narrow rectangular section than the circular. This is borne out by experiment.

Thus, tests with a slot in fiber 1/8 in. x 1¾ in. and 1 in. long showed that 2,100 volts per in. could be interrupted at 450 amperes. The circular section hole of the same area would have a diameter of 0.53 in., and from Fig. 9 such a hole would be able to interrupt only 400 volts per in. It follows then that while the circular section may be best from the standpoint of convenience of manufacture and for tube strength, it is the worst from the standpoint of circuit voltage interrupting capacity.

VIII. THE PRACTICAL PROBLEM OF EXPULSION FUSES

The curve of Fig. 9 would suggest that in order to make a successful fuse of a length regarded as practical and having a desired circuit voltage interrupting capacity, it is necessary only to use a section of sufficiently small dimensions, but difficulties of a mechanical nature intervene and prevent the solution from being reached so easily. The hole must be small enough to take care of intermediate currents of the order of 300 or 400 amperes, as indicated by Fig. 6, but if so small a hole is used, the gas generation for large currents of the order of a few thousand amperes becomes so intense that enormous pressures are produced which burst any practical and sufficiently inexpensive tube. Also the volume of flame issuing from the tube is so great that it becomes difficult to control, and there is great danger of flashover of nearby live apparatus as well as likelihood of failure of the fuse by flashover outside the tube. If the tube section is made large enough so that for large currents such danger of excessive pressures is avoided, as well as difficulties due to the large volume of flame, then the arc fails to be

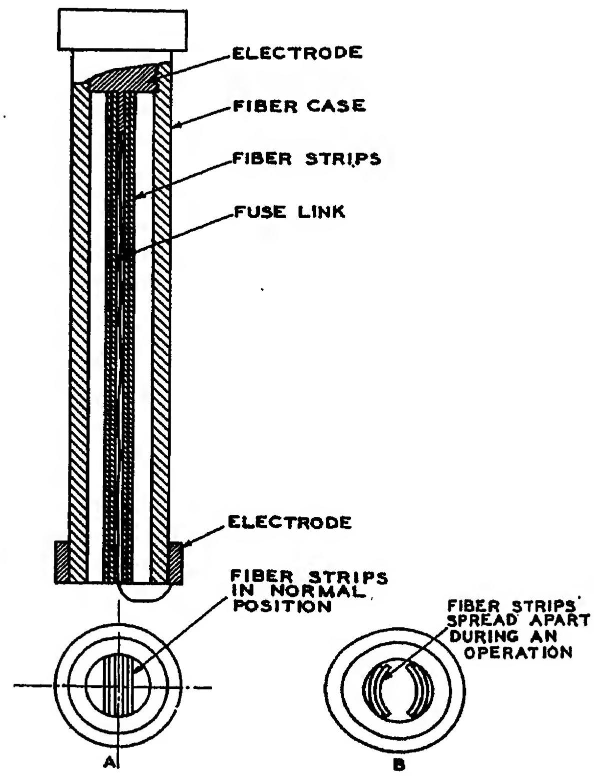

FIG. 10—HUFFSTUTTER VARIABLE CHAMBER EXPULSION FUSE

extinguished for smaller currents. One way of overcoming these difficulties would be to use a construction which would offer a small hole capable of interrupting the smaller currents, but at the same time offering a large hole for the larger currents so as to prevent unduly large gas pressures and large volume of flame. There is room for much ingenuity in devising such a construction. An example of such a construction, with which good results were obtained by Mr. Huffstutter, is shown in Fig. 10. Thin fiber sheets are placed in the tube parallel to a fuse wire, as shown in Fig. 10A.

For small currents, the section is that of the narrow slot. For larger currents, however, the pressure forces the sheets apart as in Fig. 10B, and the section is that of a large hole with a resulting decrease in the volume and pressure of the gas generated.

IX. Flame Suppression—Complete Closing of Fuse Tube

As mentioned in the preceding section, the flame issuing from an expulsion fuse is a hazard in that it has low dielectric strength and will cause flashover of any live apparatus which it may bridge around. It is entirely possible to place at the open end of the tube a flame suppressor which will deionize the ejected gas and make it harmless. The principle of construction of such a suppressor has been previously described.[4] Suffice to say here that the passage of the gas through narrow slots so that all parts of the gas come close to surfaces of solids, will very thoroughly and quickly deionize it. Of course, the use of such a device will raise the pressure in the fuse tube, and sufficient total cross-section of slots should be used in the flame suppressor to permit exit of the gas without too great rise of pressure in the tube. Fig. 11 shows the construction of a flame suppressor which was used successfully with expulsion fuse tubes.

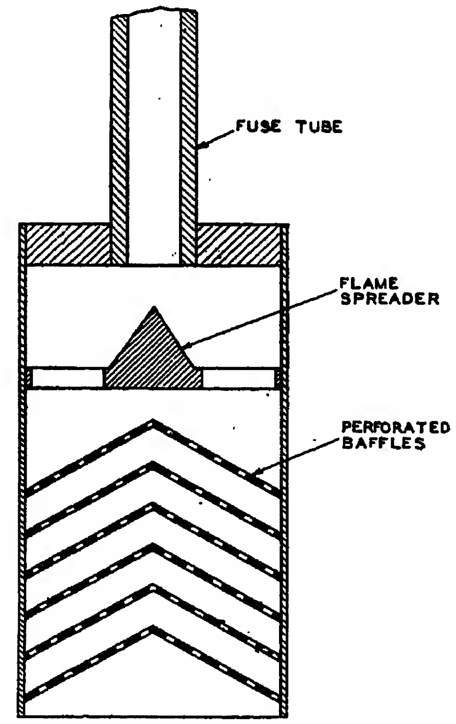

Fig. 11—Flame Suppressor

Boric acid as a fuse tube liner has been found to be better than fiber, in that its circuit voltage interrupting capacity *versus* ampere curves lay higher. In connection with its use there is an additional very remarkable possibility not at all possessed by fiber. The gas given off by the boric acid is water vapor which is easily condensable to a liquid, whereas the principal gases arising from the decomposition of fiber are permanent and condense to a liquid only under very high pressure and at very low temperature. Hence, if means are included within the tube for condensing the water vapor generated, it is possible to close up completely the boric acid lined tube without the development of excessively high pressures. Such a tube was constructed experimentally and is illustrated in Fig. 12. It was able to interrupt all currents up to 3,800 amperes at 6,900 volts, which was all the power available in the test set at that voltage and interrupted 5,000 amperes at 4,600 volts without any sign of distress due to pressure. The operation was extremely quiet, and even at the highest current there was no visible flame whatsoever and only a slight muffled sound indicated that the fuse had operated.

X. Insulating Requirements of Gas Generating Material

As ordinarily used in expulsion fuses, after the extinction of the arc, the undecomposed gas generating material must withstand the full circuit voltage with the passage of little current. It must therefore be a good insulator. Furthermore it must be a good insulator not only when cold, but also when at the high temperature at which rapid decomposition takes place,

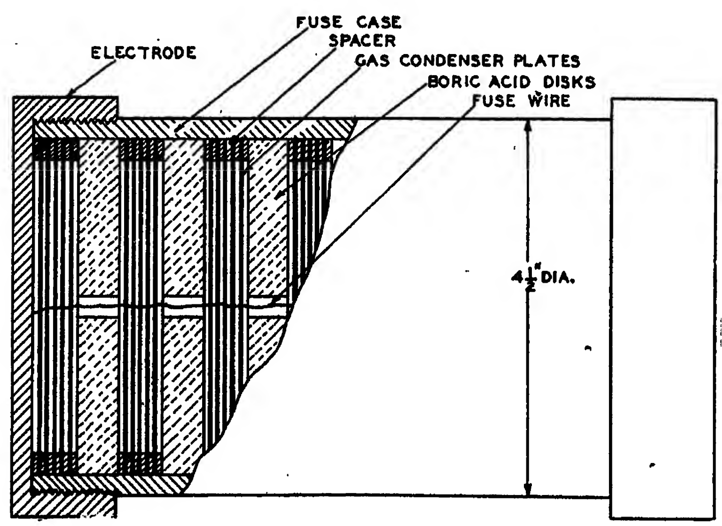

Fig. 12—A Boric Acid Totally Enclosed Fuse

since the surface of the material will be at this high temperature at the moment arc extinction takes place.

This explains why boric acid is more effective than other inorganic materials which are superior to it from the standpoint of volume of gas generation per unit of arc energy. Boric acid has a high resistivity even at a temperature of several hundred degrees C at which it decomposes rapidly. As an example of a gas generating material which from its constitution would be expected to be superior to boric acid from the standpoint of volume of gas evolution but which when tested in an

expulsion fuse appeared to be much inferior as to voltage interrupting capacity,[3] we may take ammonium alum, $Al_2\ (NH_4)_2\ (SO_4)_4\ 24H_2O$. Ammonium alum, while a good insulator when cold, melts at 89 deg. cent. and becomes a good conductor. It loses all its water of crystallization at 120 deg. cent., so that this may be taken as the temperature for rapid decomposition. Hence in an expulsion fuse using ammonium alum, the surface left immediately after the arc extinction will be an electrically conducting film of the molten salt. Under voltage this film will break by boiling and restart the arc.

It is possible to separate the gas generating and insulating requirements by suitable constructions. Thus an effective ammonium alum fuse could be made by interspersing short lengths of soapstone, as an insulating material in the tube lining of ammonium alum.

Acknowledgment

The authors wish to acknowledge their indebtedness to Mr. J. W. Huffstutter who furnished much of the experimental data used in this paper and also to Mr. A. P. Strom for his contributions on the totally enclosed boric acid fuse.

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Discussion

L. P. Boll: There is one point which I believe should be elaborated upon especially so when the operator of rural lines and his conditions are considered. The paper treated more or less the action of the expulsion type fuse link under the heavier short-circuit conditions, while the operator of rural lines is primarily concerned with the action of the fuse under abnormal conditions of load which are slightly in excess of the minimum fusing current of the fuse link. The advantage of using tubes of various bores was brought out. The operator in order to minimize his stock and to eliminate several of the difficulties encountered with having various bore cartridges, has chosen to use only two sizes of cartridges. One to accommodate fuse links from one ampere to 30 amperes and the other from 30 amperes to 100 amperes. Naturally satisfactory performance can only be obtained within a small range.

With a small amperage fuse link there are not sufficient gasses generated to create the pressure or cause sufficient turbulence to separate the burned ends of the fuse link sufficiently far to prohibit the reestablishment of the arc, after a period of time, say 2 or 3 hours, due to leakage along the fiber tube. To overcome this shortcoming of the expulsion type fuse it is necessary to surround the link by a small bore cartridge or to use a spring type fuse link. In the case of the spring type fuse link when it is melted, under any degree of short-circuit current the burned ends are mechanically separated, in fact, the entire link is ejected from the cartridge. This permits the maximum clearance between the contact which can be provided by the cartridge.

The writer has had the occasion to inspect a large number of cartridges which have been destroyed in the field. In practically every case, where there was sufficient evidence left, it could be readily seen that the leakage inside of the tube was the cause of the destruction, due to the fact that the burned ends of the link were not separated sufficiently.

The Theory of Oil-Blast Circuit Breakers

BY D. C. PRINCE*
Fellow, A.I.E.E.

Synopsis.—Analyzing the oil-blast theory, data are presented to show effect of time and carbon on oil dielectric strength, correlation between voltage recovery rate and required oil velocity, lack of correlation between either current and voltage and necessary oil velocity, correlation between recovery rate and pressure in explosion chambers. Tests on various explosion chamber forms and photographs of the oil blast in action are presented.

* * * * *

THE oil-blast theory of oil circuit breaker operation has been presented in a previous paper.[1] This theory was rather sharply challenged. The proof presented at that time was somewhat circumstantial, although no more circumstantial than the proof of other theories presented in the past. The oil-blast theory can be substantiated by direct experiment. It is the purpose of this paper to present the evidence at present available in support of this theory; some of this has been published in a fragmentary manner.[2,3,4,5]

The essence of the oil-blast theory is that arc interruption is brought about by interposing between the circuit breaker electrodes, a wall of solid oil which grows at such a rate as to be always more than sufficient to resist puncture by the recovering voltage across the circuit breaker terminals. This growing barrier of oil sweeps before it the arc products so that phenomena of deionization occurring in the gases enveloping the arc do not influence the extinction phenomena. The problem presented in this way may be broken down into its elements, namely:

1. The rate at which the voltage appears across the circuit breaker terminals.
2. Dielectric strength of oil.
3. Necessary velocity of oil.
4. Means of securing that necessary velocity of oil.

The rate at which the voltage appears across the circuit breaker terminals is susceptible of accurate determination. Such rates have been calculated and checked by cathode ray oscillograms.[6,7]

The dielectric strength of oil is, of course, well known, although its variations with different sorts of contamination and with time have not been covered by published data. Tests have been made to determine the effect of short time application of the potential on oil using both fresh oil, filtered and dried, and oil which has been used for a considerable time in an oil circuit breaker so that it contains more or less water and carbon. Fig. 1 shows the variations in the strength of oil with variations in the length of time of impressed potential. These tests were made with a gap consisting of a 1-in. disk and a cone 1 in. in diameter by ½ in. high spaced at 0.025 in. The points at the extreme right are 60-cycle values for this gap. From the figure, carbonized oil sample No. 8 has a dielectric strength at 60 cycles of $\frac{2.4}{17} = 0.14$ compared with 1.00 for clean oil sample No. 1. For a recovery voltage wave reaching its crest in eight microseconds, the ratio is $\frac{27}{42} = 0.64$ that is, from about one seventh the strength at 60 cycles, the poor oil is more than half as strong as good oil for eight microseconds and is 1.6 times better than clean oil under 60-cycle potential tests. This explains why

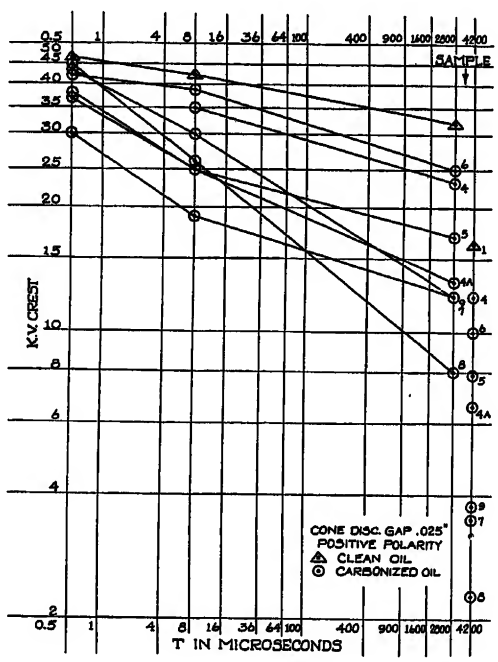

FIG. 1—BREAKDOWN STRENGTH OF OIL UNDER IMPULSE

△ Clean dry oil sample
⊙ Carbonized oil sample

moderate oil deterioration does not have a serious effect on oil-blast circuit breaker performance and also why in the quantitative analysis of the oil-blast theory, the value of 55.0 kv. per 1/10 in. as an oil dielectric strength under oil-blast circuit breaker conditions, which was found, might be expected. Both high strength and small deterioration effects are explained on the assumption that the contaminating elements operate to produce chains of carbon or moisture or both which bridge part of the gap. These chains require time for their formation. This time is not

*General Electric Co., Philadelphia, Pa.

1. For references see Bibliography.

Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 25-29, 1932.

available when a sudden application of voltage is made. It also follows that with a high velocity of oil, such as occurs in an oil-blast circuit breaker, the turbulence will tend to prevent the formation of these chains, thus assuring the maximum effectiveness even of contaminated oil in carrying out the actual interruption. These tests are being continued in an effort to ascertain quantitatively the effect of known amounts of moisture and carbon separately and in combination. Sufficient data are not yet available to construct a quantitative paper on this subject but it is hoped that it can be covered more completely at some time in the future.

Having ascertained the rate at which voltage appears across circuit breaker terminals and the dielectric properties of oil under the time conditions represented by such an application of voltage, it should be possible to calculate the rate at which oil must be introduced to interrupt a circuit having a given voltage recovery rate. It should also be possible to ascertain by direct

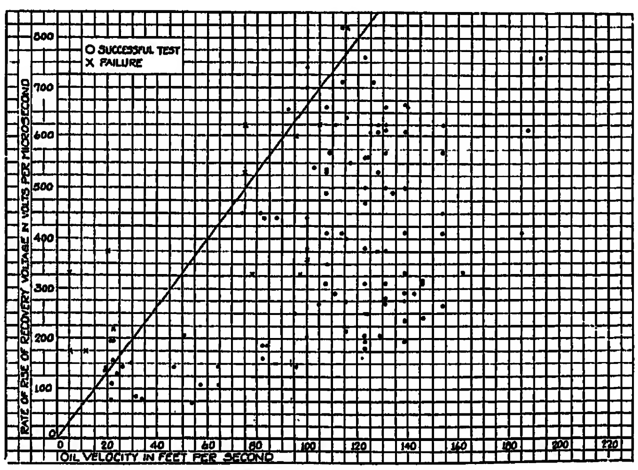

Fig. 2—Tests Showing Correlation between Rate of Voltage Recovery and Oil Velocity for Successful Operations

tests whether the interruption occurs as would be predicted by this theory. This has been done.[2] A circuit breaker was constructed in which oil was driven into the gap between the contacts by a piston. The velocity of the piston movement was measured and was varied over a considerable range.

A large number of interrupting tests was made. During the series, the test conditions were varied as follows:

1. Change in oil velocity. Range from 5 to 200 ft. per second.

2. Change in test voltage. Range from 3,800 volts to 13,200 volts.

3. Change in current interrupted. Range from 200 amperes to 30,000 amperes.

4. Change in rate of recovery voltage rise. Range from 60 to 820 volts per microsecond.

All of the tests made are plotted in Fig. 2 with rate of recovery voltage rise in volts per microsecond as ordinates and oil velocity in feet per second as abscissas. All other variables are ignored in this plot except that successful tests, namely those on which interruption occurred at the first current zero of arcing, are marked with a dot. By studying the distribution of the points with and without dots, it is possible to draw a line dividing the region of points with dots from that without dots. The slope of this line should be proportional to the dielectric strength of oil under the conditions of circuit breaker interruption and should correspond to the strength of oil measured under the corresponding short time conditions. In this case, the actual slope of the line corresponds to a dielectric strength of 55 kv. per 1/10 of an inch, which is of the proper order for short time voltage applications. To state the case mathematically:

(1) The circuit has a recovery rate of

$$\frac{v}{t} = \text{volts per second}$$

(2) Oil has a dielectric strength of

$$\frac{v}{l} = \text{volts per inch}$$

To ascertain the necessary oil velocity, divide one of these fractions by the other, securing the equation

$$\frac{\frac{v}{l}}{\frac{v}{t}} = \frac{l}{t}$$

where $\frac{l}{t}$ is the required oil velocity. There is thus a positive proof that the oil-blast theory is at least one explanation of the behavior of this circuit breaker. So far, however, the possibility that some other explanation might cover the same set of observations has not been excluded.

To secure evidence on that point, the tests shown in Fig. 2 are further classified in Fig. 3 in order to examine the data for a possible relation of test voltage to the behavior of the breaker. In this chart, test voltages are plotted as ordinates and oil velocity in feet per second as abscissas. Here again successful tests are marked with dots. Those tests not marked with dots are those in which interruption did not occur at the first current zero of arcing. If the test voltage and not rate of recovery voltage rise were predominant in affecting the performance of the breaker, it would be expected that the points indicating successful tests would be so distributed on the chart that some relation to test voltage would be indicated. A study of the chart, however, shows that the points showing successful tests are mixed at random with the unsuccessful tests. It is therefore concluded that there is no relationship between oil velocity and test voltage.

From the analysis so far made, there still exists a

possibility that the amount of current interrupted and the oil velocity might bear some definite relationship. To study such a possibility, another chart, Fig. 4, was made. This differs from Fig. 3 in that currents interrupted in amperes are shown as ordinates. The identification of successful tests is the same as that used in Figs. 2 and 3. From this chart, it will be easily

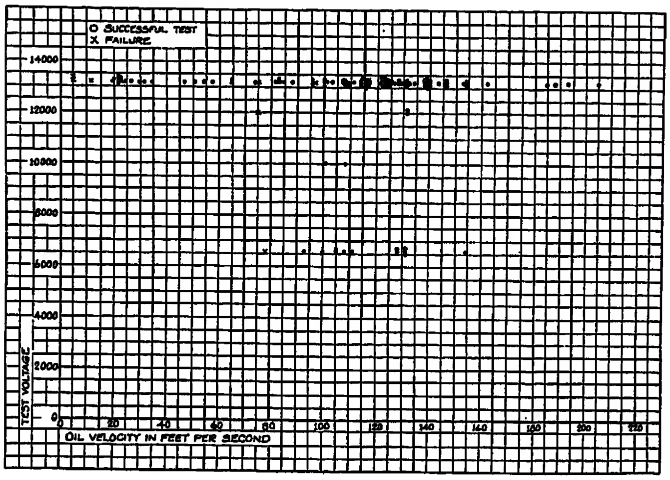

FIG. 3—TESTS SHOWING LACK OF CORRELATION BETWEEN VOLTAGE AND OIL VELOCITY FOR SUCCESSFUL OPERATIONS

seen that the successful and unsuccessful tests are so intermixed that it is not possible to consider that either of them is in any way related to the amount of current interrupted. This discussion, therefore, definitely bears out the conclusion already stated that oil velocity bears a definite relationship to rate of recovery voltage

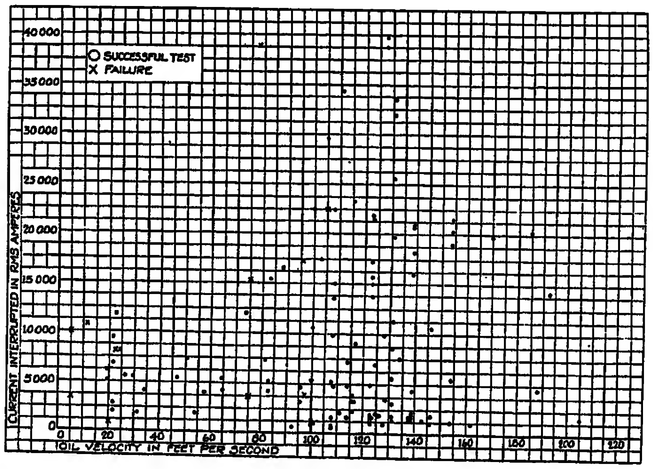

FIG. 4—TESTS SHOWING LACK OF CORRELATION BETWEEN CURRENT AND OIL VELOCITY FOR SUCCESSFUL OPERATIONS

rise and that when the proper oil velocity for a given recovery voltage rise has been determined for successful operation, the breaker performs successfully over a wide range of test voltages and amounts of current interrupted.

Indirectly, these data bear upon the subject of deionization. If our phenomenon were one of deionization, a longer time should be required to deionize the dense ionization of a heavy current test than the sparse ionization accompanying a light current interruption. With this design of circuit breaker, there is no element tending to produce more rapid or efficient deionization at a high current where more ionization is present, than at a lower current where little ionization is present and yet no apparent difference appears traceable to this cause.

In the large number of tests made with this circuit breaker, no effort was made to change the oil frequently. The oil thus varied over wide limits as to its 60-cycle puncture value. However, no considerable difference seems to have been produced by this difference in the 60-cycle value of the oil. This result would be expected from the tests already described in which the strength of oil under impulse was measured.

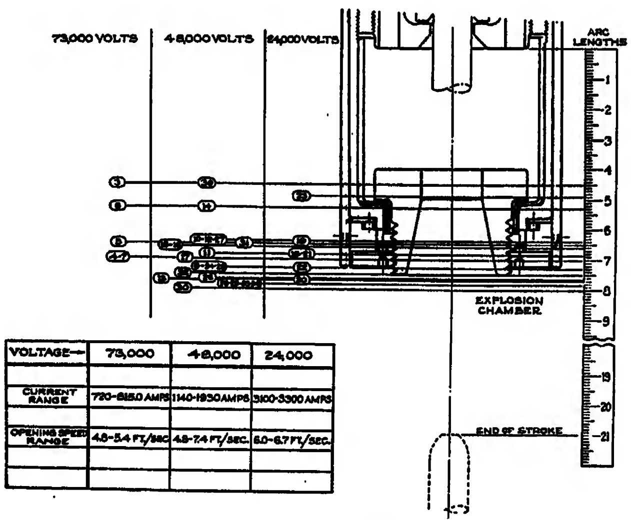

FIG. 5—SKETCH SHOWING ACTION OF EXPLOSION CHAMBER AT VARIOUS VOLTAGES AND CURRENTS

Once evidence has been secured that the oil-blast theory of operation quantitatively explains the operation of an impulse (oil driven by piston) type of circuit breaker and that other general explanations of circuit breaker behavior are not applicable, it is much more difficult to prove that this same theory of operation explains the behavior of other types of oil circuit breakers. Reasonably direct proofs can, however, be obtained in the case of explosion chamber types of breakers. If these breakers really operate as oil-blast breakers, then steps taken to promote a blast of solid oil will produce an improvement in performance.

Fig. 5 represents a large number of tests with a plain explosion chamber and shows that the arc is uniformly extinguished in the region where the oil-blast action should be most pronounced. At the throat the pressure head has all been turned into velocity head so that there is very little pressure tending to prevent solid oil from displacing the arc products at the current zero.

A special explosion chamber was constructed as shown in Fig. 6 so arranged that there was a series of throats between which there were pockets of oil. This arrangement had the advantage over the simple explosion chamber in providing three points at which the current zero might occur under most favorable conditions of oil-blast. With this arrangement, the arc lengths and arcing time were found to be uniformly less than with the simple explosion chamber.

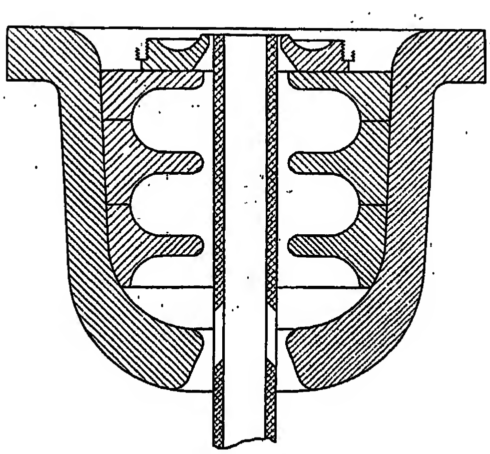

Fig. 6—Multiple Throat Explosion Chamber

In another test, the arc was drawn in a narrow slot, the sides of which were smooth. In this case, performance was notably inferior even to a plain open break circuit breaker. A series of hollows was then cut out in the sides of the slot, thus approximating the explosion chamber arrangement of Fig. 6. The performance was immediately improved to approximately the same as Fig. 6. The porosity of the wall material was not found to influence performance.

If the oil-blast explosion chamber operated exactly in accordance with the quantitative theory proven in the case of the impulse type of circuit breaker, there should be a correlation between pressure shown in the explosion chamber and the rate of recovery voltage rise across the circuit breaker contacts. Some test data have been analyzed and Fig. 7 made up from the data. In this figure, pressure and rate of recovery voltage rise are coordinates. It is not possible to measure the oil velocity directly and due to the wide variation in back pressure, there is not a direct relation between the measured pressures and oil velocity. However, it is apparent that at least some correlation exists between the explosion chamber pressure and the rate of recovery volts at the time of arc interruption. In order to break down this problem into one susceptible of a complete solution, it is necessary to find first the relation between the arc energy and the amount of gas evolved from an arc and second, the conditions governing arc energy. Considerable progress has already been made on the first half of the problem. A large amount of data are available showing that within the error of plus and minus 50 per cent the amount of gas formed is equal to

$$V = 0.07\,W$$

V = volume in liters at normal temperature and pressure

W = arc energy in kilowatt seconds

The amount of arc energy, however, is quite variable in existing types of breakers. This is necessarily the case in a device which interrupts in one or two half cycles of arc inasmuch as the contacts may separate at any point in the cycle. The arc will be interrupted at the first zero after a certain pressure has been reached, but if the current zero does not occur for a considerable time after this pressure has been attained, the pressure will continue to increase to an unnecessary degree. The higher speed of the breaker, the greater will this variation be in per cent, that is, the amount

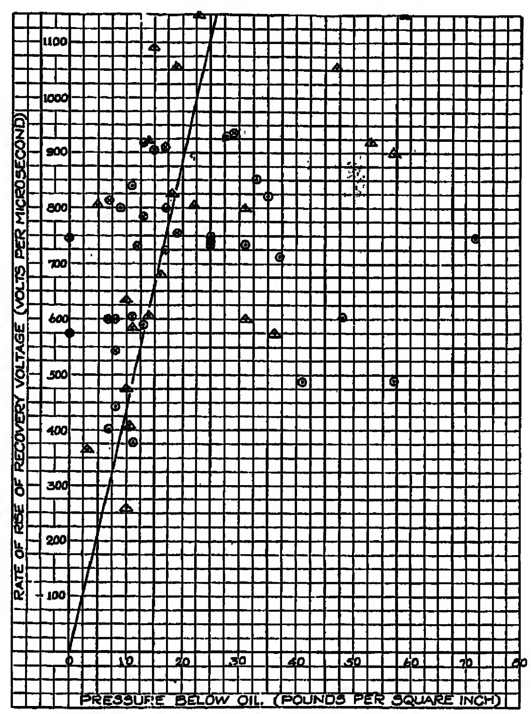

Fig. 7—Tests Showing Correlation between Rate of Voltage Recovery and Explosion Chamber Pressure at Time of Interruption

○ Tests on oil-blast FH-203
△ Tests on oil-blast FK-44
● Pressure when circuit cleared
× Pressure at current zero at which the circuit did not clear

of time represented by a variation of one cycle becomes large by a comparison with the total arcing time. Steps are being taken to make tests with a synchronous closing and opening device which should make it possible to produce and select the type of wave, that is, symmetrical or displaced at the time of contact parting. Tests with this apparatus should make it possible to ascertain what part of the variations in arc energy and therefore pressure are due to the circuit variables and

what part still remains to be accounted for as due to the vagaries of the arc.

Statements[8,9] have appeared in the press to the effect that carbon particles are instrumental in arc extinction. Our own tests did not bear this out inasmuch as tests made with liquids which carbonize freely, other things being equal, show less effective arc interrupting properties.

In an attempt to satisfy pardonable skepticism as to the operation of oil-blast breakers by the insertion of walls of solid dielectric, a considerable number of photographic studies has been made. Fig. 8 taken from an article by Mr. E. B. Noel[5] shows the oil in the

FIG. 8—OIL-BLAST EXPLOSION CHAMBER OPERATION

act of interrupting an arc and washing away the arc products. The illustrations taken by Mr. Noel were taken at the rate of 128 per second and therefore do not represent definite times after the current has been interrupted. Efforts are being made to photograph conditions a very short time, such as 10 to 50 microseconds after the current zero. The problems of technique in securing such photographs have not yet been overcome although there is hope of securing such a record. Even over an interval of 1/128th of a second including the current zero, no marked change appears other than the disappearance of the arc. The arc is clearly subjected to violent washing action in Fig. 8c and 8d and, by Fig. 8e, clear oil is flowing between the electrodes.

In the foregoing, the author has attempted to bring in all relevant information which may bear on the oil-blast theory either to prove or disprove it. It is felt that in the case of impulse breakers, the exact quantitative results obtained by measuring the oil dielectric strength under impulse conditions and the operation of the breaker under known oil velocity and recovery rate conditions prove beyond question that this breaker operates on the oil-blast theory as enunciated and in no other way. All of the factors discovered in connection with the other types of circuit breakers appear to confirm the same law, that is, variations in geometry tending to promote oil-blast action improved performance. Configurations tending merely to hold oil in the vicinity of the arc do not promote operation. Such pressure measurements as can be taken on an explosion chamber of the oil-blast type clearly resemble the velocity measurements made with the impulse breaker pointing to the same conclusion, although the perfection of the proof is less quantitatively exact. Illustrations of the oil-blast breaker in action confirm the oil-blast theory.

As pointed out last year,[10] the ability of a circuit breaker to interrupt a circuit does not depend altogether on whether its designer understands its theory of operation. However, it is a great help in design to have a correct and preferably quantitative theory of operation. The oil-blast theory has proven most useful as evidenced by the wide variety of applications which it has made possible.[11]

Acknowledgment is made to Messrs. O. R. Schurig and B. H. Thompson for the data on gas formation; to Messrs. C. M. Foust and R. F. McAtee for the data on impulse strength of oil; and to Mr. W. F. Skeats and his staff for the test data and cooperation in the preparation of this paper.

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11. *Practical Application of the Oil-Blast Principle of Circuit Interruption*, R. M. Spurck, see page 171 this issue.

Discussion

For discussion of this paper see page 191.

Practical Application of the Oil-Blast Principle of Circuit Interruption

BY R. M. SPURCK*
Associate, A.I.E.E.

Synopsis.—The oil-blast principle of circuit interruption may be applied to oil circuit breakers of many types which cover a wide range of service, voltage and interrupting requirements. Although the mechanical construction and configuration of the interrupting elements varies widely for varying requirements, nevertheless the same principle of operation applies.

It is shown that the oil-blast utilized for efficient arc extinction may be produced electrically by decomposition of oil or mechanically by a spring driven piston in an oil cylinder. Whichever of the two methods is employed, comparable performance results.

Several types of breakers which operate on the oil-blast principle are described and test data given. In all designs of breakers on which the new principle has been used, marked reductions in arc duration and arc length result, even at the higher rates of recovery voltage rise. The principle is therefore applicable to breakers of the high speed type.

THERE were presented to the Institute last year, three papers[1,2,3] which announced the development and practical application of the oil-blast explosion chamber to high-voltage oil circuit breakers. Another paper[4] in this issue also discusses the results of further research on the operation of the oil-blast theory. The research work was performed concurrently and in close coordination with the development of new lines of oil circuit breakers which utilize the oil-blast principle of circuit interruption. It is the purpose of this paper to describe the construction of these new breakers, to give results of interrupting tests made on them, and to discuss their characteristics.

It should be brought out first that the oil-blast principle of circuit interruption is not confined to any particular type of breaker, limited to any voltage, or restricted to any specific design. Developments so far completed apply the oil-blast principle to breakers of various types and designs, generally described as follows:

1. High-voltage outdoor breakers of the downward break type in which the oil-blast explosion chamber is used on each breaking contact.

2. Moderate-voltage indoor and outdoor high-interrupting-rated breakers of the downward break type with two breaks per pole. In this design, an oil-blast explosion chamber is used on each breaking contact.

3. Moderate-voltage moderate-interrupting-rated indoor breakers of the downward break type with three poles in one tank. In this application in a three-phase breaker, one chamber surrounds the contacts of all three poles.

4. Moderate-voltage high-interrupting-rated indoor breakers of the upward break type having two breaks per pole in individual oil vessels. Such breakers are commonly known as the "H" type. In this case, new baffles designed to give an oil-blast are applied.

5. Moderate - voltage moderate - interrupting - rated outdoor breakers of the downward break type with two breaks per pole in individual tanks. One chamber surrounds the pair of contacts in each tank.

6. An entirely new superspeed, 15,000-volt design of single-phase breaker for railway service. In this design, one break in one oil vessel is used. The oil-blast is obtained mechanically.

As has been brought out in previous papers, the oil-blast principle is based on the following conception of its operation. An oil circuit breaker interrupting an alternating current circuit will interrupt the circuit at any current zero after the contacts part if sufficient insulation is inserted between the contacts at current zero to resist puncture by the recovery voltage that appears across the contacts at that time. The rate and magnitude of recovery voltage rise at various operating voltages and conditions has been predicted by mathematical calculations[3,5] and checked by cathode ray oscillograms. Also, by experiment and mathematical analysis,[6] the oil velocity necessary to cause interruption at an early current zero at various rates of recovery voltage rise and oil velocity required for early arc extinction, has put into the hands of designers what may be termed as new tools that enable them to construct apparatus of greater efficiency and consistency of performance than was heretofore possible. Furthermore, with such definite and broadly applicable data available, the designers had opened to them a wide field of application which was limited only by their own ingenuity in devising schemes for applying the new principle. There follows a general description of the various applications that have been made.

Application to High-Voltage Outdoor Breakers

The oil-blast explosion chamber as applied to high-voltage breakers was described in papers[1,2,3] presented last year so no further reference will be made to it here.

Application to Downward-Break Indoor and Outdoor Moderate-Voltage High-Interrupting-Rated Breakers

The explosion chambers used to apply the oil-blast principle to the downward break tank type moderate-

*General Electric Co., Philadelphia, Pa.

Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 25-29, 1932.

voltage indoor and outdoor breakers having each pole in a single tank are somewhat different in design from the chambers used in the high-voltage outdoor breakers. In these breakers, smaller chambers are used. At such voltages, also, the necessity for high insulation disappears so it is possible to use a metal chamber, properly insulated inside and out, and provided with an insulating throat bushing. Two types of chambers are used, one having high pressure butt contacts, the other segmental sliding contacts and gates. The chamber with the butt contacts is used in breakers where the normal current carrying requirements are not more than 1,200 amperes, in which case no contacts in addition to those on which the arc is broken, are required. Such an explosion chamber is shown in cross section on Fig. 1. As in the high-voltage breakers, an auxiliary gap is provided but due to limitations of space, the mechanical details are somewhat different although the operation is the same.

Because of the similarity of the operation of this chamber to the one used on the high-voltage breakers, no test results will be given. It may be stated, however, that the arc lengths and durations obtained on breakers equipped with it are uniformly very short. As an example, on tests at 23,000 volts, arc durations of approximately 1½ cycles are the rule.

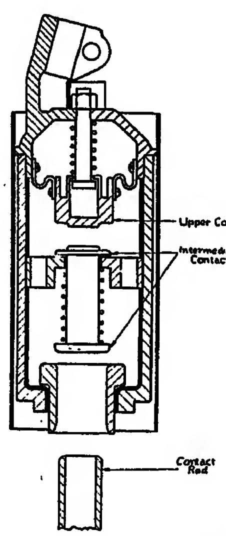

Fig. 1—Oil-Blast Explosion Chamber for Moderate Voltage Downward-Break Indoor and Outdoor Breakers for Current Ratings Up to 1,200 Amperes

Contacts in partially opened position

In breakers of normal current ratings in excess of 1,200 amperes, the arc interrupting contacts must be bridged by additional current carrying contacts and both the main and arcing contacts so designed that in opening the circuit, current will be transferred from the main contacts to the arcing contacts before interruption begins. Such a design is shown in Fig. 2 which shows the contacts in three positions as described.

When the arcing contacts are in the closed position, Fig. 2A, they are bridged by main current carrying contacts. As the breaker opens, the main contacts part before the moving arcing contact separates from its fixed contact, thus transferring all current flow to the arcing contacts. In the position shown in Fig. 2B, the moving arcing contact has separated from the stationary contact a sufficient distance to permit closing of the metal gates. In this position, an arc plays between the stationary contact, metal gates and moving contact.

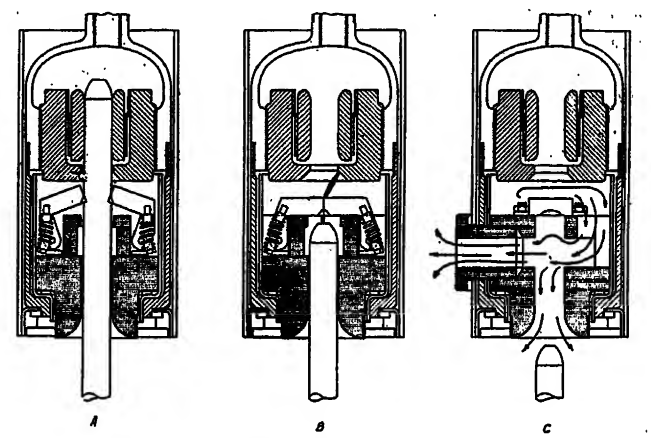

Fig. 2—Oil-Blast Explosion Chamber for Moderate Voltage Downward-Break Indoor and Outdoor Breakers of Current Ratings Above 1,200 Amperes

A. Contacts closed
B. Contacts partially open
C. Contacts open
Note Section *C* is turned 90 deg. from Sections *A* & *B*

During this phase of the interruption, the arc in the chamber above the gates creates pressure that causes oil to flow rapidly into the passage below the gates in Fig. 2B. Note that Fig. 2C is a section rotated 90 deg. from Fig. 2B. The flow of oil passing through the arc path below the gates causes circuit interruption at an early current zero.

Table I shows a few of a series of tests made on such

TABLE I

Volts Kv.	Current Interrupted Amperes	Equivalent Three-Phase Kva. Interrupted	Arc Duration Cycle	Arc Length Inches
44	4,100	310,000	1.4	2.8
44	4,200	325,000	1.2	2.5
44	3,600	275,000	1.4	2.8
44	2,500	195,000	1.4	2.8
44	2,500	195,000	2.0	3.8
44	1,300	100,000	1.7	2.8

Single-phase interrupting tests at 60 cycles on gated explosion chamber shown in Fig. 2—arc durations and lengths include both gaps. Recovery voltage rate 1,600 to 1,800 volts per microsecond. Arc durations and lengths include both gaps.

a chamber. All of these tests are circuit interrupting tests. Although the maximum pressure in the explosion chamber was about 80 lb. per sq. in., the pressure above the oil in the tank was very low in all tests. Because of the short arc durations, contact burning and oil deterioration were negligible.

Inasmuch as rate of recovery voltage rise plays an important part in the interrupting performance of breakers, all test data herein will include a statement of recovery voltage rise rate. In some tables of data, it will be noted that a range of recovery voltage rise is given. This range primarily results from changes in circuit reactance made to control the value of short circuit current. Recovery voltage rise rates as high as those listed do not occur in regular practise except in

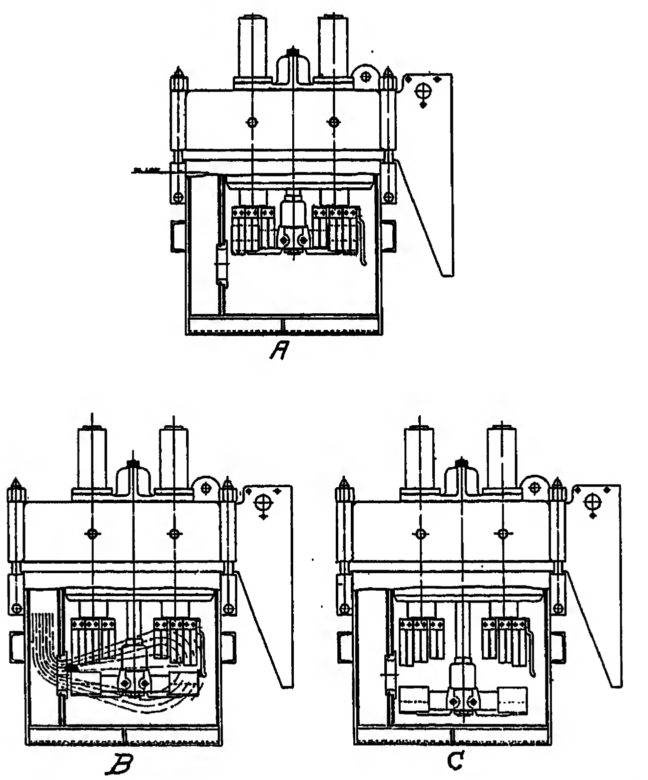

FIG. 3—OIL-BLAST PRINCIPLE APPLIED TO INDOOR 15,000-VOLT DOWNWARD-BREAK BREAKERS HAVING THREE POLES IN ONE TANK

A. Contacts closed
B. Contacts partially open
C. Contacts open

cases where a breaker on a single feeder from a generator bus interrupts a short circuit at a point on the feeder near the stations.

APPLICATION TO DOWNWARD-BREAK INDOOR MODERATE-INTERRUPTING-RATED BREAKERS

So far, the description of applications of the oil-blast principle has included designs in which explosion chambers are used. The application of the principle is, however, not limited to explosion chamber type breakers but is also applicable to the smaller breakers of moderate interrupting ratings in the range of from 50,000 to 250,000 kva. at voltages up to and including 15,000 volts. In applying the principle to such breakers of the downward break tank type in which all three poles of a three phase breaker are in one tank, a box of insulating material inside the tank surrounds the entire group of contacts. The top of the box is just below the oil level. Three of the sides of this box fit the inside of the tank, the fourth side of the box adjacent to one set of contacts is set away from the tank and opposite each contact is an opening in the side of the tank. The arrangement of this box in the tank is shown in Figs. 3 and 4 which should be referred to in the following description of the operation of the breaker.

As the contacts part, the decomposition of the oil by the arc forms gas which creates pressure in the insulating box and causes oil to flow out of the orifices in the side of the box spaced away from the tank. These orifices are so placed that the flow of oil is past the contacts and the arc adjacent to the orifices. Therefore, the arc products in the contact gaps adjacent to the orifices are being continuously washed away and out through the orifices so that at an early current zero, when no decomposition is taking place, the space between the stationary and moving contacts is filled with clean oil, the insulation of which is sufficient to

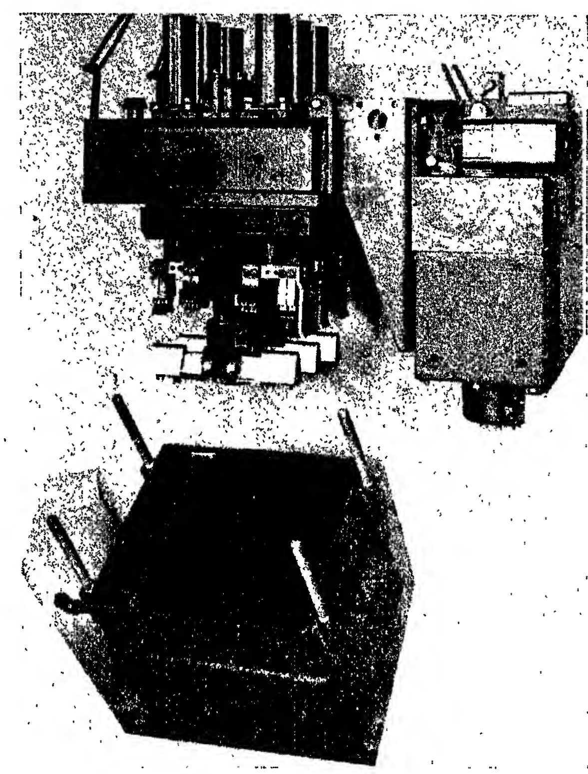

FIG. 4—COMPLETE 15,000-VOLT INDOOR BREAKER WITH OIL-BLAST DESIGN SHOWN IN FIG. 3

prevent the recovery voltage from breaking down the gap and continue arcing.

In the design of these breakers are a number of interesting features, for example, with the box enclosure, any pressure in the box acts on the three operating rods which pass through the top of the box and tend to reclose the breaker. To compensate for this tendency to close, pistons of an area somewhat greater than the combined area of the operating rods are at-

tached to the cross tie at the bottom of the moving contacts and extend through the bottom of the box. The result is that the pressure in the box exerted on the larger area of the lower pistons gives a definite opening tendency for all pressures inside the box. Another design feature worthy of mention is the arcing horn on the pressure building contacts, that is, the ones adjacent to the box wall with no opening. The purpose of this horn is to curtail box pressure produced by the pressure building gap. To understand this, it must be realized that only a small gap is required to produce sufficient pressure to cause an adequate blast of oil across the actual interrupting contacts which are adjacent to the openings in the box. On the other hand, a somewhat longer gap may be required in the interrupting contacts. As the two gaps without the arcing horn would normally be the same for each increment of travel of the contact blade, the horn is provided to limit the pressure producing gap to a value that is sufficient to provide only proper oil-blasting pressure necessary to accomplish arc extinguishment at an early current zero by the insulation introduced in the interrupting gap.

TABLE II

Volts	Current Interrupted Amperes	Kva. Interrupted	Arc Duration Cycles	Arc Duration Length Inches	Time from Trip Impulse to Interruption Cycles
4,200	30,000	218,000	0.7	1.3	3
4,200	850	6,200	1.0	0.3	6½
4,200	1,700	12,400	0.6	0.3	7
4,200	5,900	42,900	1.0	0.3	7
4,200	15,000	109,000	1.0	0.3	7½
4,200	26,000	189,000	0.7	0.3	6
4,200	49,000	356,000	0.6	0.3	5
4,200	53,000	385,000	0.2	0.3	4½

Three-phase 60-cycle interrupting tests on an indoor 15,000-volt downward break breaker of the type shown in Fig. 4—rate of recovery voltage rise 500 to 11,000 volts per microsecond.

Maximum arc lengths and durations of the three phases recorded. Arc duration and lengths include the interrupting gap only.

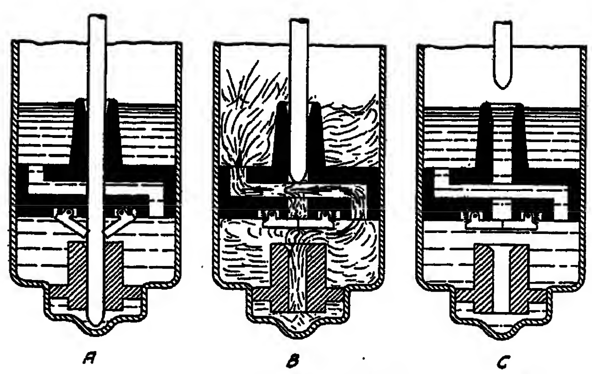

Fig. 5—Sequence of Operation of Contacts of Upward-Break Moderate Voltage Indoor Breaker During Circuit Interruption

A. Contacts closed
B. Gates closed—breaker partially open
C. Contacts open

Table II shows some of a series of interrupting tests made at 4,200 volts on a 15,000-volt breaker of this type. If the arc durations shown in this table are compared with arc durations of plain-break breakers previously used in the interrupting and voltage range covered by this line of breakers, it will be found that in general the arc durations of these new breakers are from 75 per cent to 85 per cent shorter. This shortening of the arc duration effects a marked reduction in the oil deterioration and contact burning.

Application to Upward-Break Indoor High-Interrupting-Rated Breakers

Breakers of the upward break type having two tanks per pole and commonly known as the H type are especially well adapted to the application of the oil-blast feature.[7] The interruption action illustrated in Fig. 5 is so similar to that described for the gated explosion chamber that further description is considered superfluous.

In Table III are listed some of the interrupting tests made on one of these breakers. The arc durations in this table are from 50 per cent to 80 per cent less than the arc durations in breakers with the older type of baffles. These reduced arc durations and the correspondingly lessened contact burning permit increases in interrupting ratings in these breaker structures.

TABLE III

Test	Volts	Current Interrupted R.M.S. Amperes	Kva. Interrupted	Arc Duration Cycles	Arc Length Inches
CO	14,500	2,400	60,300	1.2	2.5
CO	14,500	1,400	35,200	1.8	3.7
CO	14,500	16,400	412,000	0.5	1.2
CO	14,500	16,600	417,000	0.6	1.0
CO	8,400	1,740	25,300	0.6	1.0
CO	8,400	27,000	393,000	0.5	1.0
CO	8,400	44,000	640,000	0.6	1.5

Three-phase 60-cycle interrupting tests on a 15,000-volt 2,000-ampere *FH* oil circuit breaker with cross blast baffles shown in Fig. 5.

Maximum arc length and duration of the three phases are recorded.

Rate of recovery voltage rise 1,000 to 1,600 volts per microsecond.

Arc durations and lengths include both gaps.

Application to Downward-Break Moderate-Interrupting-Rating Moderate-Voltage Outdoor Breakers

Another line of breakers to which the oil-blast principle has been applied[7] is that comprising 15,000 volt outdoor breakers in interrupting ratings from 50,000 kva. to 175,000 kva. In these breakers, each pole is contained in a separate tank. The general construction and operation are, however, similar to those described for the indoor 15,000 volt moderate interrupting rated breakers previously described. It is therefore considered sufficient to include Fig. 6, a cross section of one tank.

As to tests, those shown in Table IV are typical. Also, as the arc durations are comparable with those

already listed for other breakers and the comments regarding performance apply, they will not be repeated.

Application to Single-Phase Super-Speed High-Speed Outdoor Breakers

In all of the breakers so far described, the oil-blast resulted from oil decomposition by a pressure producing gap. The same effect can be produced by mechanical means as will be shown in the following description of

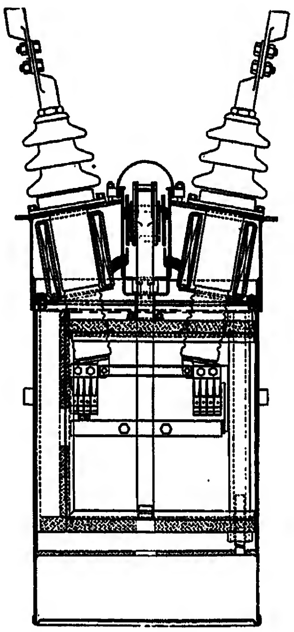

Fig. 6—Oil-Blast Principle Applied to Outdoor Moderate-Voltage Downward-Break Breaker with Each Pole in One Tank

Contacts partially open

TABLE IV

Volts Kv.	Current Interrupted Amperes	Kva.	Arc Length: Cy. of Arc	Arc Length: In. per Brk.	Time from Trip Impulse to Inter. Cyc.
13.2	1,500	34,300	1.7	0.8	9.0
13.2	5,100	117,000	1.5	0.8	8.5
13.2	8,500	194,000	0.6	0.5	6.0
13.2	8,900	203,000	0.6	0.5	6.0
13.2	9,600	219,000	0.6	0.5	6.0

Three-phase 60-cycle interrupting tests on the downward break 15,000-volt outdoor breaker with oil blast feature shown in Fig. 6.
Rate of recovery voltage rise 1,400 volts per microsecond.
Arc durations and lengths included only the interrupting gap.
Maximum arc lengths and durations of the three phases are recorded.

a 15,000-volt single-phase breaker designed for single-phase 25-cycle, 12,000-volt railway service requiring that 50,000 amperes at 12,000 volts be interrupted in one cycle or 0.04 second.[8]

In this case, a piston acting in a cylinder containing oil is used in place of the pressure gap to inject the blast of oil into the gap between the interrupting contacts. Fig. 7 shows the interrupting element of one of these breakers with the contacts in the closed and opening positions. When interrupting a short circuit, the spring-charged mechanism pulls the contacts apart at the same time the piston moves downward. The baffle around the moving contact directs the oil flow created by the piston movement over the stationary contact upward through the hollow contact rod into the air chamber. The path of the rapid stream of oil is thus directly through the arc path so that at the first current zero, further flow of current is prevented by the high insulation of the oil that has replaced the arc products.

Quick tripping of this breaker is obtained by the utilization of a very simple mechanism which is re-

TABLE V

Test Volts	Current Peak Values	Current Interrupted Amperes	Arc Duration Cycles	Short-Circuit Duration Cycles
12,000	3,900	2,500	0.15	0.5
12,000	24,000	14,000	0.35	1.0
13,200	30,000	18,000	0.30	1.0
13,200	20,000	13,000	0.45	1.0
13,200	35,000	24,000	0.30	0.5
7,000	65,000	39,000	0.40	1.0
7,000	73,000	47,000	0.30	0.5

Interrupting tests outdoor at 25 cycles single phase on high-speed breaker with oil blast features shown in Fig. 7.
Rate of recovery voltage rise—range 400 to 800 volts per microsecond.

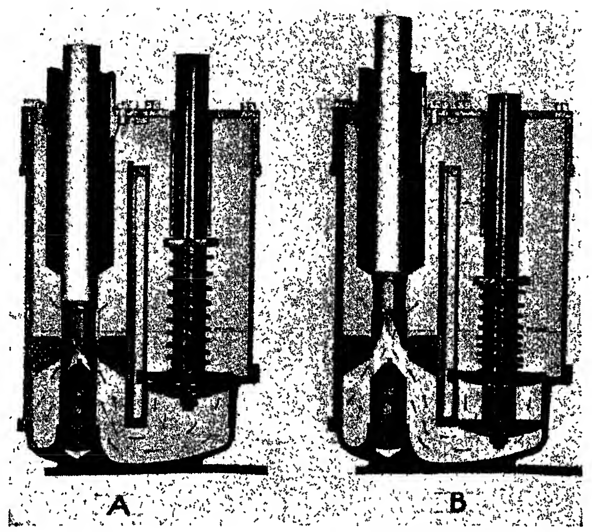

Fig. 7—Interrupting Element of a 15,000-Volt 1,500-Ampere Breaker Designed to Interrupt 50,000 Amperes in 0.04 Second at 25 Cycles

Oil-blast obtained mechanically
A. Contacts closed
B. Contacts during arcing period

leased to open by means of a magnetic tripping mechanism of the type used on high-speed air breakers.[9]

Table V shows data on a few of a series of 49 tests made on one of the 12,000-volt high-speed breakers. After the first 31 tests at currents interrupted ranging from 2,500 to 18,000 amperes at 12,000 or 13,000 volts, the contacts were examined and found to be only moderately burned.

After the 31st operation, new oil and contacts were put in the breaker. Then after six interruptions, a series of 12 tests was made at 12,000 volts and currents interrupted ranged from 21,000 to 35,000 amperes. The time interval between tests varied from 15 to 40 seconds. After these tests, the contacts were only moderately burned. The oil tested 12.2 kv. in a standard gap.

The points worthy of emphasis in the performance of this breaker are that the mechanically created oil-blast which gives short arcing times can be readily combined with a mechanism and trip which operate so quickly that the short circuit can be interrupted at the first current zero after the short circuit begins. This rapid clearing occurs at both low and high currents interrupted.

Conclusions

The oil-blast principle of circuit interruption has been applied to oil circuit breakers for high and low voltages and small and large interrupting ratings. Parts can also be supplied to apply this principle to many types of breakers already in service. Although the mechanical construction of the interrupting elements may vary for different requirements as is shown by the ability to obtain the results either mechanically or electrically, nevertheless the fundamental principle of operation is the same.

Breakers equipped with oil-blast show consistently short arc lengths and unusually short periods of arc duration, even at the higher rates of recovery voltage rise and over wide ranges of current interrupted. The result is that contact burning and oil deterioration are so minimized that the maintenance required is greatly reduced.

In many types of breakers to which oil-blast has been applied, it has been possible to increase the interrupting rating of the structure. Many types of breakers already in service may be modified to incorporate the oil-blast feature and obtain high-speed operation. Also, in the newer designs, the interrupting capacity per unit volume is much greater than that previously obtained.

The rapid arc-extinction characteristic of the oil-blast design makes it admirably adaptable to breakers requiring high speed of operation. Such high speed improves system stability, minimizes system voltage dips, and improves service in many other ways.

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Discussion

For discussion of this paper see page 191.

Recent Developments in Arc Rupturing Devices

BY R. C. VAN SICKLE*
Non-member
and
W. M. LEEDS*
Non-member

THE deion grid method of arc rupture has been very successfully applied during the past two years to the design of an extensive line of arc rupturing devices for oil circuit breakers of all voltage classes. The soundness of the fundamental theory underlying this development has been amply demonstrated by the remarkable improvement in operation shown by circuit breakers of every voltage class when designed according to this principle. This paper discusses later developments in this theory, describes the newest types of arc rupturing devices embodying this principle, and presents results obtained with them in special tests and during operating service in the field.

THEORY

The fundamental operating principles and the structural arrangement of the deion grid have been discussed in previous papers before the Institute,[1,2] but recent developments in arc rupturing phenomena make it desirable to review briefly the manner in which this device, Figs. 1 and 2, functions to extinguish an arc. The separation of the circuit breaker contacts draws the arc in a narrow slot open at one end and filled with oil.

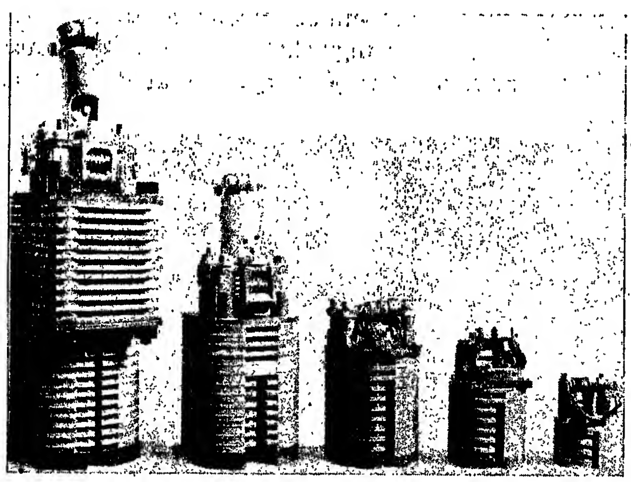

FIG. 1—DEION GRIDS SIZES *A*, *B*, *C*, *D* AND *E* FOR OUTDOOR OIL CIRCUIT BREAKERS

At intervals through the stack of plates making up the grid, there are interspersed plates of magnetic material which surround the slot on three sides and so modify the magnetic field of the arc as to produce a force which not only keeps the arc within the slot but also moves it back into a series of oil pockets. The intense heat of the arc vaporizes and decomposes the oil, generating gas which can escape only through the open end of the slot. In doing so the gas must pass through the arc stream, subjecting this ionized path to a continuous turbulent blast of fresh un-ionized gas. Furthermore, since this generation of gas is continuous throughout the full length of the arc, the deionization due to the automatic gas blast takes place not alone in some selected portion of the arc but continuously and evenly throughout its entire length. The magnetic blowout is used to advantage in this device by applying the forces so as to control and hold the arc without appreciably lengthening it.

According to the theory recently discussed by Slepian

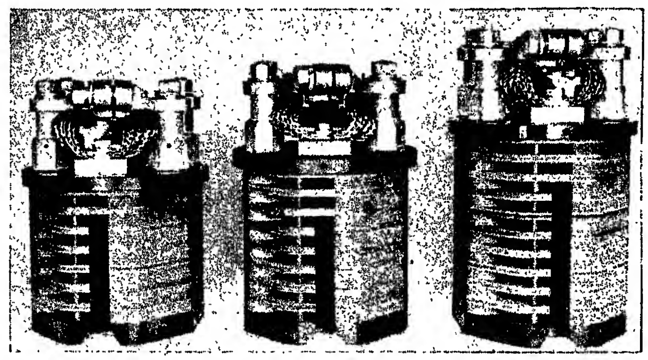

FIG. 2—DEION GRIDS FOR 34.5 KV., 46 KV. AND 69 KV. MADE OF *C* SIZE UNITS

before the Institute[3] and given experimental confirmation by Browne,[4] the turbulent condition of the arc stream causes the arc to be broken up into many parallel arcs of very small cross section, so that the complete stream may be considered as a number of fine threads swirling about in tumultuous motion, these threads being highly ionized and carrying most of the current. At the current zero, diffusion from these slender threads of intense ionization into the fresh un-ionized gas all about them causes the whole arcing space to assume almost immediately a comparatively uniform low ion density so that in a very few microseconds dielectric strength of perhaps twenty times the arc voltage is established between the contacts. Further deionization due to recombination and diffusion continues, aided by the gas blast, but it is the extremely rapid initial rate of recovery of dielectric strength that makes possible the interruption of an arc under unusually difficult circuit conditions. It is evident that a high degree of efficiency is obtained with deion grids since all of the gases generated are caused to pass directly through the arc stream in order to escape. It is thus possible to produce a high rate of deionization in the arc path with a minimum amount of gas generated and a correspondingly small amount of energy liberated within the circuit breaker tank.

*Westinghouse Elec. & Mfg. Company, East Pittsburgh, Pa.
Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 25-29, 1932.

Application

Previous discussions before the Institute[2,5] have set forth the constructions by which these principles have been applied in high voltage, outdoor circuit breakers from 34.5 kv. to 230 kv., and this paper describes the later developments applying the same principles to the 15 kv. and 23 kv. outdoor breakers, particularly the low capacity breakers for automatic reclosing service, and to the power house class of oil circuit breakers at 15 kv. For purposes of comparison, representative grids for different voltage applications are shown in Fig. 1. It will be noted that the grids are essentially stacks built up from a number of units, each unit consisting in turn of thin plate elements of insulating and magnetic materials. These plate elements are designed in five different sizes, designated by the letters *A* to *E* and each applicable within a certain range of voltage. The size of the plate varies roughly with the voltage rating in which it is applied, the largest plate being used for the highest voltage. The number of units in each stack is varied according to voltage requirements as may be seen from Fig. 2 in which three grids for different voltages are shown built up from plates of the *C* size.

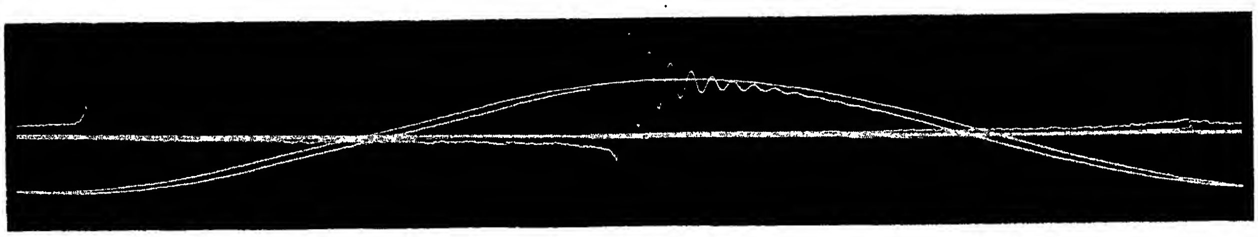

Fig. 3—A Cathode Ray Oscillogram of a Single-Phase Interruption by *A* Grids of 3,300 Amperes at 132 Kv.

It will be apparent on reflection that in applying the grids over this wide range of service voltages, many diverse conditions are encountered and many different aspects of the problem must be solved. For instance, in the power industry today circuit breakers with rupturing capacities up to 2,500,000 kva. are required both at 15,000 volts and at 230,000 volts, as well as at the intermediate voltages, but the magnitudes of the currents interrupted at this kva. rating differ widely at the two extremes of voltage. At 230 kv. the current interrupted per phase is less than 6,500 amperes while the voltage per contact break is very high. The outstanding problem in operating service at this voltage is one of system stability under short-circuit conditions and the desirability of any circuit breaker for such service is gaged by its ability to interrupt short circuits with a minimum duration of arcing. Therefore, the grid for such service must be inherently a voltage device and all the elements of its design must be shaped to the purpose of building up dielectric strength in the arc path at the highest possible rate in order to prevent fast-rising, high recovery voltages from restriking the arc after a current zero.

At 15,000 volts the conditions are quite different. The voltage per contact break is comparatively low and presents no great difficulties for the modern oil circuit breaker. System disturbances due to voltage surges constitute an operating problem of relatively minor importance and the desirability of any circuit breaker for this application is measured, not by the shortness of its arcing period alone, but by its ability to interrupt heavy short circuit currents without emitting oil or flame and without mechanical injury to its operating parts. The breaker must also be able to withstand a reasonable number of repeated cycles of duty without impairing its adequacy for normal switching service immediately afterward. Since the short-circuit current per phase in this service approaches a maximum of 100,000 amperes, the grid for such an application must be inherently a current rupturing device with its parts so designed that an arc will be drawn only to the length at which it can be extinguished most advantageously with a minimum amount of energy liberated. It must also dissipate the gases which are formed and protect the circuit breaker itself from damage due to the presence of high powered arcs.

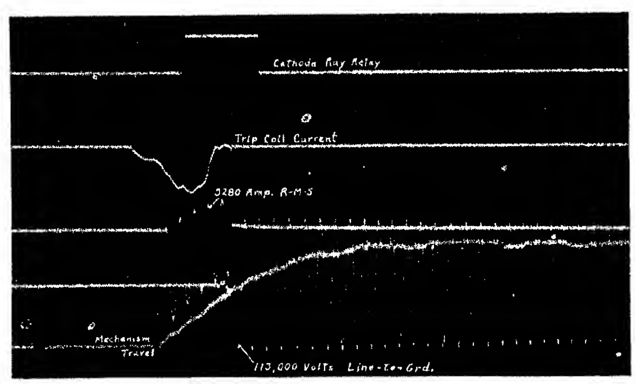

Fig. 4—A Magnetic Oscillogram Corresponding to Fig. 3

The varied, and in some cases conflicting, requirements for this wide range of service have been met and circuit breakers equipped with deion grids are now available in nearly every breaker class. These grids are all similar and vary gradually from high capacity, high voltage or *A* size to the low capacity, low voltage or *E* size. They are the result not only of the application of a theory, but also of extensive testing and development in both field[6,7] and laboratory. The use of a cathode ray oscillograph is of great assistance in

studying the arc voltage since it records the phenomena accurately on a large time axis. One cycle on a cathode-ray oscillogram, Fig. 3, occupies as much distance on the time axis as 75 cycles on a corresponding magnetic oscillogram, Fig. 4.

The length of all of these grids, while graded to the voltage for which they are designed, is such that arc extinction ordinarily takes place before the movable arc-drawing contact is half way down the grid. This large factor of safety is provided for two reasons; first, to insure adequate rupturing ability in the event of a breaker being subjected to unusually difficult circuit conditions involving extraordinarily rapid rates of rise of recovery voltage, or of its being unwittingly subjected to excessive overvoltages; second, to provide for any possible loss of effectiveness of one or more of the uppermost units in the grid due to unusual duty in the form of a prolonged series of repeated heavy current interruptions without an opportunity for inspection. It will be noted that each individual unit in the grid starts to produce its own horizontal gas blast as soon as the arc reaches it, so that the longer the arc, the greater the number of units which are brought into play against it. A great advantage is thus obtained over any device that restricts its deionizing activity to one or at most two points of the arc.

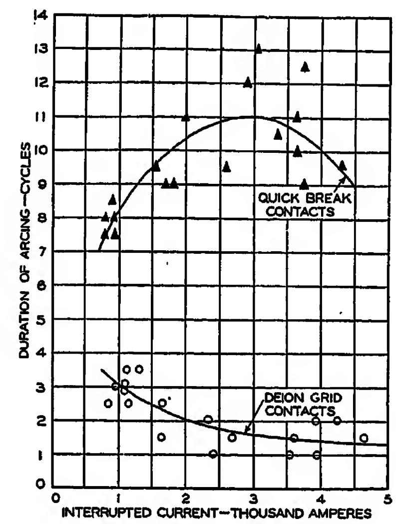

Fig. 5—Curves Showing the Reduction in Arcing Time on a 66-Kv. Circuit by Substituting Deion Grids for Quick-Break Contacts

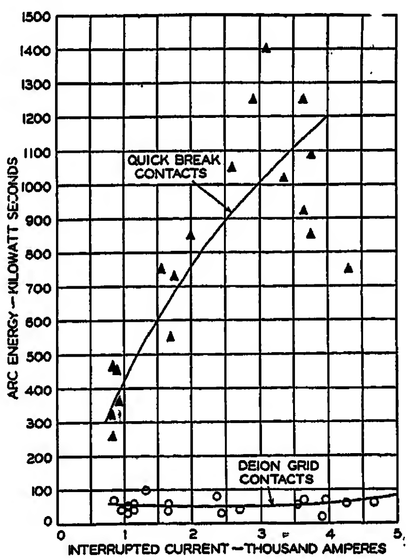

Fig. 6—Curves Showing the Reduction in Arc Energy on a 66-Kv. Circuit by Substituting Deion Grids for Quick-Break Contacts

The remarkable improvement in the interrupting characteristics of the outdoor breakers resulting from the replacing of plain or quick break contacts by deion grids is illustrated by several representative curves taken from laboratory tests. Fig. 5 shows that the duration of arcing on a 66-kv. circuit was reduced to between one-fourth and one-seventh of the former arcing time by the use of deion grids. This result is of great importance in connection with the effect of short-circuit duration on system stability. For the same series of tests, Fig. 6 shows that the arc energy with deion grids was only 5 per cent to 10 per cent of the values associated with conventional quick break contacts. This means a corresponding reduction in contact depreciation and oil deterioration and makes possible long periods of service without maintenance to the breaker.

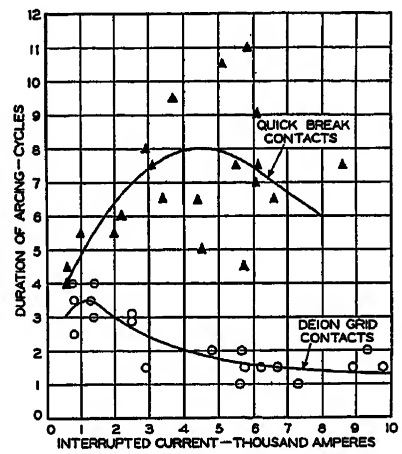

Fig. 7—Duration of Arcing at 38 Kv. Before and After Installing Deion Grids in an Oil Circuit Breaker

Tests on a 38-kv. circuit gave the results shown in Figs. 7 and 8. The deion grids used in these tests were of the *C* size and the improvement over the old style contacts is just as pronounced. The duration of arcing is shortened about 75 per cent while the arc energy is reduced to less than 10 per cent of the value with quick break contacts. It should be remembered that all of these tests were made on a low power factor laboratory circuit involving a much higher rate of rise of recovery voltage than is usually found in actual service in the field. Even better performance of the circuit breakers

is to be found under average operating conditions as is confirmed by the data given later in this paper:

Automatic Reclosing Feeder Breakers

In the class of circuit breakers for automatic reclosing service on distribution feeder circuits there is a growing demand for breakers which may be subjected to repeated cycles of interrupting duty without requiring any maintenance. These breakers are also required to reclose after clearing a short circuit with a much smaller

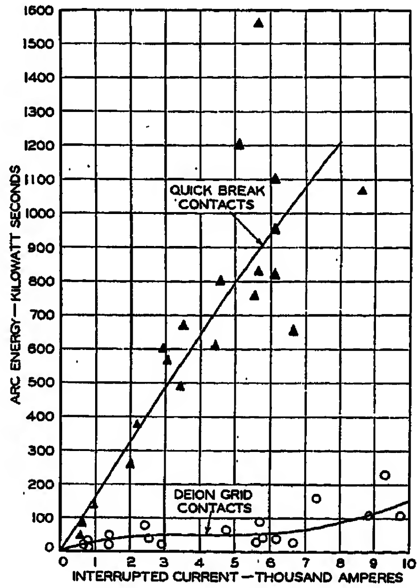

Fig. 8—Arc Energy at 38 Kv. Before and After Installing Deion Grids in an Oil Circuit Breaker

time interval than the two minutes provided for in the standard duty cycle. The excellent characteristics of moderate capacity deion grid circuit breakers designed for this type of service have been demonstrated by many series of tests similar to the following.

A 15-kv. oil circuit breaker equipped with *E* size deion grids was subjected to a series of 21 short circuits of approximately 14,000 amperes at 3,810 volts, the duty cycle consisting of one *CO* plus two *OCO* tests at

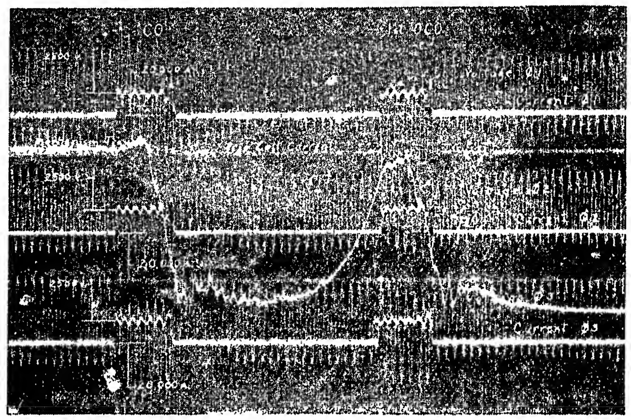

Fig. 9—Oscillogram of a *CO-OCO* Part of a Series of 21 Successive Interruptions Made on a 15-Kv. Deion Grid Oil Circuit Breaker Equipped for Automatic Reclosing Service

zero and 120 second time intervals. The complete series of tests occupied only 45 minutes, during which time the tanks were not even lowered for inspection of the contacts. The data for these tests are given in Table I. The interrupted current varied from 12,200 amperes to 15,300 amperes, while the breaker closed against currents from 15,000 amperes to as high as 28,800 amperes during the *OCO* tests. The oscillogram in Fig. 9 shows an average of between 1.0 and 1.5 cycles of arcing on a frequency of 60 cycles per second and indicates a breaker time from the instant the trip coil was energized until the arc was extinguished of about six cycles. It will be noted that the initial reclosure occurred only 24

TABLE I—15-KV. DEION GRID OIL CIRCUIT BREAKER RECLOSING TESTS AT 3,810 VOLTS—THREE PHASE—UNGROUNDED—60 CYCLES DUTY CYCLE: *CO*—0 SECONDS—*OCO*—120 SECONDS—*OCO*

			CO		1st *OCO*			2nd *OCO*	
Test No.	Time of test p.m.	Phase No.	Interr. current amp.	Duration of arcing cycles	Current closed amp.	Interr. current amp.	Duration of arcing cycles	Current closed amp.	Interr. current amp.	Duration of arcing cycles
29853	5:20	1	13,500	2.0	28,800	14,400	1.0	27,200	14,400	1.0
		2	12,800	2.0	26,800	12,300	1.5	21,300	12,300	1.0
		3	13,300	1.5	16,800	12,700	1.5	18,300	12,700	1.0
29854	5:30	1	14,400	1.5	22,400	13,400	2.0	21,500	15,300	1.5
		2	12,800	1.0	17,100	12,400	2.0	18,800	13,600	1.5
		3	13,000	1.5	17,100	13,000	2.0	27,900	13,000	1.0
29855	5:36	1	14,100	1.0	28,000	13,600	1.5	22,400	13,400	2.0
		2	12,800	1.0	21,700	12,800	1.5	16,200	12,800	1.5
		3	14,600	1.5	16,100	12,700	1.5	23,300	13,300	1.5
29856	5:43	1	13,800	1.0	26,600	12,800	2.0	24,000	13,800	2.0
		2	13,600	1.5	17,000	12,000	2.0	16,200	13,600	1.5
		3	13,700	1.0	18,600	12,400	1.5	23,300	13,700	1.5
29857	5:49	1	13,500	1.0	21,400	13,400	2.0			
		2	12,400	1.5	15,000	12,800	2.5	No record		
		3	14,000	1.0	23,300	13,100	1.5			
29858	5:55	1	13,400	1.0	24,000	12,450	1.5	20,800	14,550	1.5
		2	13,200	1.5	20,850	15,000	1.5	24,800	13,200	1.5
		3	13,950	1.0	15,300	13,000	1.5	18,600	13,950	1.0
29859	6:01	1	14,100	1.5	19,200	12,800	1.5	24,000	12,200	1.0
		2	12,800	1.5	16,200	12,000	1.5	22,500	12,800	1.0
		3	13,600	1.5	17,400	12,400	1.5	17,100	12,700	0.5

cycles or 0.4 second after the first short circuit was cleared, this time interval being about as short as could be obtained with the reclosing relay equipment.

The breaker performed very satisfactorily during these tests. No appreciable drop in oil level was observed, the oil loss being limited to a few drops which seeped out between the operating shaft and bushing. Pressure records were obtained on several of the tests

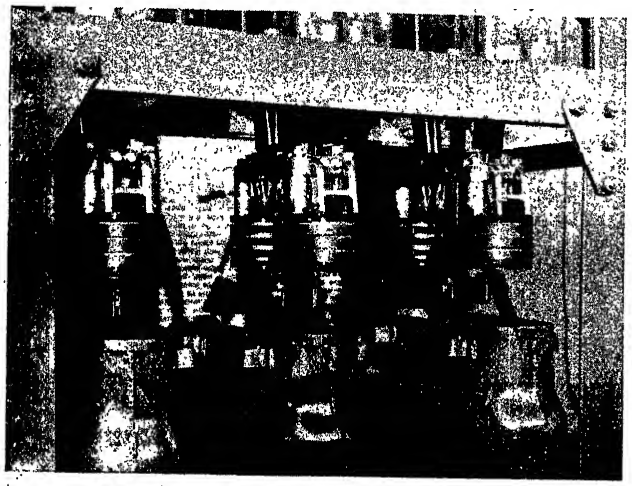

FIG. 10—THE 15-KV. AUTOMATIC RECLOSING BREAKER AFTER INTERRUPTING A SERIES OF 21 SUCCESSIVE SHORT CIRCUITS

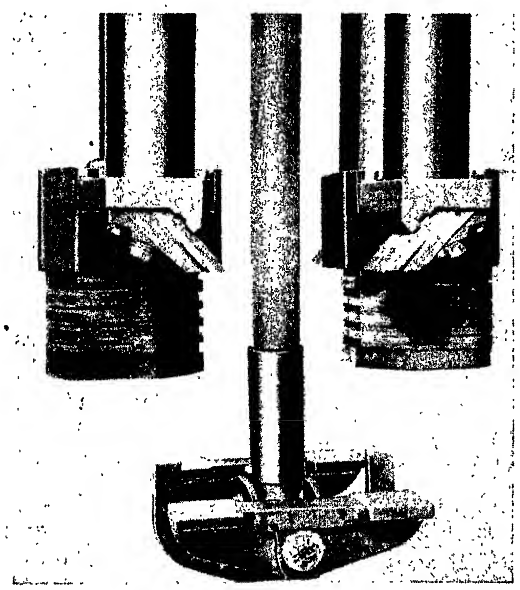

FIG. 11—HEAVY DUTY DEION GRID CONTACT ASSEMBLY FOR A 15,000-VOLT, 4,000-AMPERE POWER-HOUSE BREAKER

but the values were only about 15 pounds per square inch. Considering the severe service applied to the breaker the oil depreciation was quite moderate, the dielectric strength changing from an average value of 25.8 kv. before the tests to 11.4 kv. after the twenty-first test. When the contacts were examined at the conclusion of the tests, see Fig. 10, they were found to be in condition for further service without maintenance.

POWER-HOUSE BREAKERS

As in the case of the various classes of outdoor breakers, the application of deion grids to the power-house class of service presented its own individual problems of design. Since modern powerhouse breakers interrupt heavy short circuits with a duration of arcing close to one cycle at 60-cycle frequency, due to the effectiveness of the inherent magnetic blowout of the current loop, improvement in operation by the application of a more effective form of interrupting device is to be expected more in reduced disturbance and oil deterioration than in shorter arcing time.

In circuit breakers with deion grid contacts the arc is confined in a slot and prevented from moving rapidly by the oil trapped in the pockets. Therefore, the total length of arc is not much greater than the actual contact separation and the arc voltage is kept to a minimum.

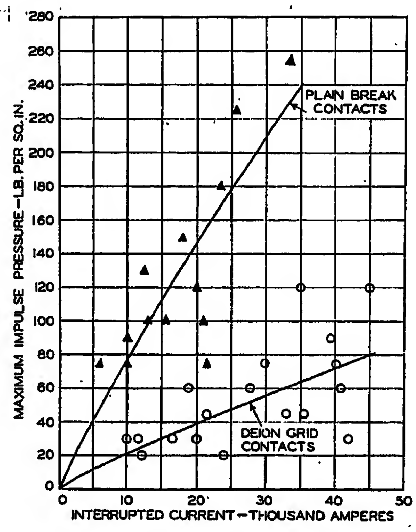

FIG. 12—THE REDUCTION IN PRESSURE DURING LABORATORY INTERRUPTING TESTS AT 13.2 KV. OBTAINED BY REPLACING PLAIN BREAK CONTACTS BY HEAVY DUTY DEION GRIDS IN POWER-HOUSE BREAKERS

This reduction in arc voltage combined with the short arcing time decreases the total amount of arc energy, resulting in turn in a smaller volume of gas generated, lower pressures, less depreciation in the dielectric strength of the oil, and less tendency for the breaker to discharge gas and oil during the interrupting process.

The requirements involved in the interruption of heavy currents at low voltage have resulted in the design of a heavy duty form of deion grid for powerhouse service, illustrated in Fig. 11. Certain details of the plate elements are modified so as to provide a more sturdy construction and to give proper means of control of the heavier current arcs. All of the insulating plates are made of fiber and are of sufficient thickness to give ample mechanical strength to the grid. Large oil pockets provide an adequate supply of oil in the grids. A vent located immediately below the top plate of the

grid relieves the initial pressure impulse as the arc first appears on the arc-drawing contacts.

It is now generally recognized that the performance of oil circuit breakers is much better when operating on commercial circuits than when connected directly to a laboratory test generator because of the lower rate of rise of recovery voltage. An oscillogram of a field test in which a plain break circuit breaker interrupted 21,000 amperes at 12,700 volts with only one-half cycle of arcing is shown in Fig. 15. On a laboratory circuit a similar breaker interrupting 23,500 amperes with 7,620

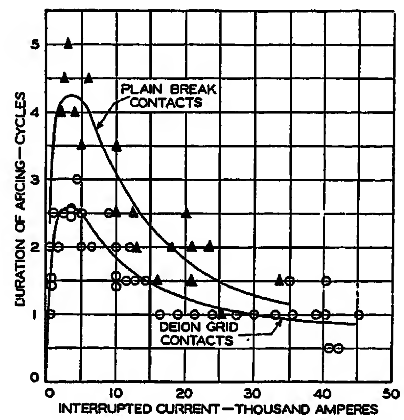

Fig. 13—Comparison Between Duration of Arcing at 13.2 Kv. with Plain Break Contacts and with Heavy Duty Deion Grids in Power-House Breakers from Laboratory Test Results

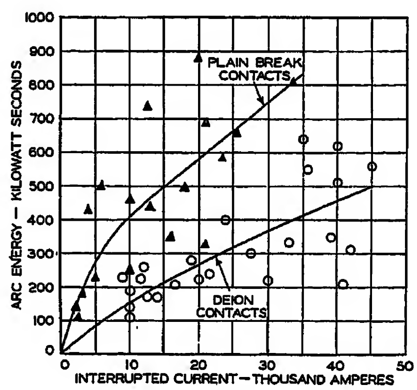

Fig. 14—Comparison Between Arc Energy at 13.2 Kv. with Plain Break Contacts and with Heavy Duty Deion Grids in Power-House Breakers from Laboratory Test Results

volts across a single pole arced for two cycles as shown by the oscillogram in Fig. 16. However, this same breaker when equipped with deion grids and tested on this same circuit interrupted 21,500 amperes at 7,620 volts across a single pole with only one cycle of arcing as is shown by the oscillogram in Fig. 17. Corresponding reductions in the pressure and in the arc energy may be seen on the oscillograms. It is evident that the results of laboratory tests, while not necessarily representative of the speed of breaker operation on the average commercial circuit, give an excellent means for comparing the performance of different types of arc rupturing devices.

By keeping down the rate of liberation of arc energy by control of the arc length and by absorbing some of the impulse in the grid structure, the maximum pressures in powerhouse breakers are actually reduced to about one-third of the values obtained with the same breaker when equipped with the conventional plain break contacts, as shown by Fig. 12. The arcing time during these tests on the difficult laboratory circuit was about 40 per cent less with deion grid contacts for currents between 1,000 and 10,000 amperes, as shown by Fig. 13. The arc energy, upon which the oil depreciation, gas generation, pressure and tendency to throw oil depend, is shown in Fig. 14 to be less than half the value with plain break contacts over the entire current range of a 1,000,000-kva. power-house breaker.

For the lower normal current ratings the arc-drawing contact acts as a main current-carrying member as well,

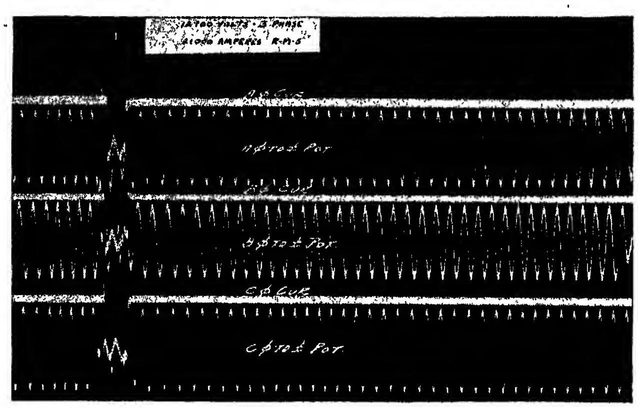

Fig. 15—Oscillogram Showing the Interruption by Plain Break Contacts of a 21,000-Ampere, 12,700-Volt, Three-Phase Short Circuit on a Large System

the arcing and main current-carrying surfaces being carefully separated in the design. The arc is drawn on surfaces of arc-resisting alloy which has five to ten times the life of copper. The breaker design with brush contacts external to the grids, used for the higher current ratings, is illustrated by the 15-kv., 4,000-ampere breaker shown in Fig. 11. These contacts have given excellent results in development tests, and brushes rated at 2,000 amperes can carry short circuits up to peak values of 200,000 amperes without indications of burning.

The principles of the deion grid method of arc rupture are now being applied to single-tank breakers in the 4,500, 7,500 and 15,000 volt classes, and improved operation comparable with that obtained on the larger power-house breakers is expected.

Tests

The results of a number of field tests on high-voltage oil circuit breakers equipped with deion grids have

TABLE II—50-KV. DEION GRID OIL CIRCUIT BREAKER SINGLE-PHASE-TO-GROUND SHORT-CIRCUIT TESTS ON A 44-KV. SYSTEM

Test No.	Type of duty cycle	Current interr. amp.	Kilovolts to ground: Before fault	Kilovolts to ground: After fault	Kilovolts to ground: During fault	Oil test: Before kv.	Oil test: After kv.	Arcing time cycles	Ground
1	CO	3500	25.5	25.6	2.2	29.0	28.4	—	Arcing
2	CO	3900	26.3	27.3	2.2	28.4	28.0	½	Solid
3	CO	4000	25.6	25.7	2.2	29.0	29.7	½	Arcing
4	CO	3900	25.6	25.6	2.5	29.8	28.0	½	Arcing
5,6,7,8	4-OCO 1 minute intervals	3915	25.6	25.6	2.2	28.0	24.8	½	Solid

already been reported.[6,7] Among the lower voltage breaker classes several series of tests of considerable interest have been made recently. The difference in operation of the breakers before and after the installation of deion grids is most striking.

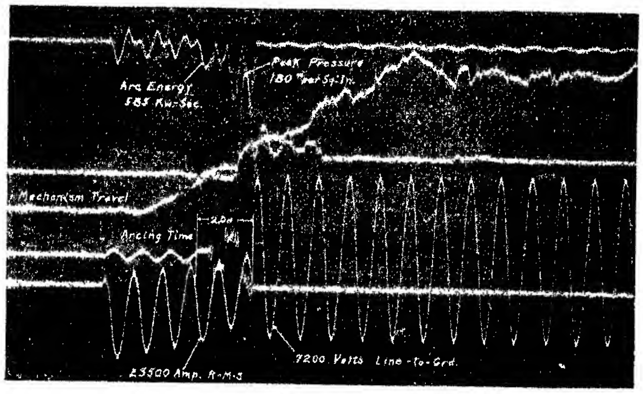

FIG. 16—OSCILLOGRAM SHOWING THE INTERRUPTION BY PLAIN BREAK CONTACTS OF A 23,500-AMPERE LINE-TO-GROUND SHORT CIRCUIT ON A 13,200-VOLT LABORATORY TEST GENERATOR

On one of the large 44-kv. systems, the interrupting duty imposed upon the breaker in a certain location was so heavy due to unusually severe circuit conditions that a single operation was sufficient to blacken the oil. Gas and oil were usually thrown from the breaker and the arc was cleared only by utilizing practically the full contact break distance.

The old style contacts in one of these breakers were replaced by deion grids and the breaker subjected to a series of interrupting tests. An extract from the tabulated data prepared by the operating company is reproduced in Table II. There was no throwing of oil and no sign of distress. The last five tests were made on one pole of the breaker, and the oil tested almost as high after the tests as before.

A smaller circuit breaker rated at 350,000 kva. at 37 kv., was equipped with deion grids and its performance determined by a series of field tests on one of the largest 26.4-kv. systems. The breaker was first subjected to a 2-*OCO* duty cycle at approximately 12,000 amperes, followed after a short interval by one *OCO* test of approximately 16,000 amperes. This last test imposed an interrupting duty of 750,000 kva. on the breaker, which was more than twice its rating with the old style contacts. Although this was rather heavy service for a breaker with 20-in. diameter tanks, there was no external disturbance on any of the tests other than a small discharge of gas from the vent. The oscillograms showed only one cycle of arcing. After the three interruptions the oil was in excellent condition, having depreciated from 28 kv. to an average value for the three tanks of between 23 kv. and 24 kv. The contacts when examined showed a negligible amount of burning and further testing was prevented only by trouble with other apparatus involved in the test set-up.

Reports have been received from various operating companies in all parts of the country that the deion grid breakers which they have in service have been giving excellent performance. High speed of arc rupture is giving better system stability. Greatly reduced oil depreciation and less contact maintenance is lowering operating costs.

After interrupting three short circuits caused by lightning on a 33-kv. system, a deion grid breaker was examined, and the only evidence of the service experienced was a small mark about the size of a pin located at a point where the contacts separated.

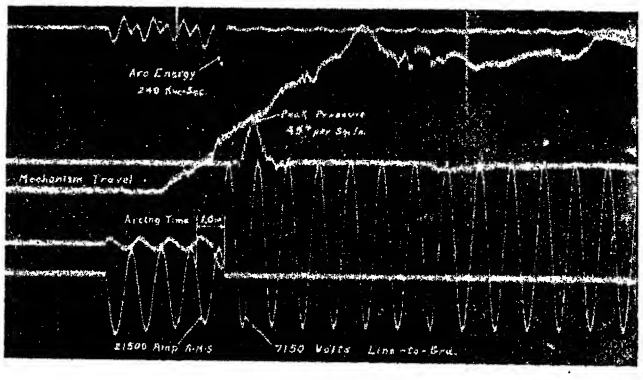

FIG. 17—OSCILLOGRAM SHOWING THE INTERRUPTION BY DEION GRID CONTACTS OF A 21,500-AMPERE LINE-TO-GROUND SHORT CIRCUIT ON A 13,200-VOLT LABORATORY TEST GENERATOR

On another system of the same voltage, eighteen short circuits were cleared by a deion grid circuit breaker before the oil, which then tested 17 kv., was changed. The same company reported that one of its 132-kv. oil circuit breakers was equipped with deion grids and

then not examined until after it had operated 21 times due to lightning surges. Although each time it had interrupted from 50 per cent to 75 per cent of its rupturing capacity, the contacts, and oil were found to be in such excellent condition that the breaker was put back into service immediately without any maintenance whatsoever.

Conclusions

The use of arc rupturing devices employing oil have many inherent advantages, and their disadvantages are being eliminated or minimized by recent developments. With modern methods of controlled arc extinction and a better understanding of the effect of external circuit conditions, uncertain operation and alarming signs of distress during even moderate rupturing duty may be considered almost a thing of the past. Of especial interest to the operating companies is the ease with which old contacts can be replaced by modern deion grids, giving to the breakers greatly improved performance at relatively small expense.

The arc rupturing devices which have resulted from the scientific analysis of the methods of arc extinction have made possible greatly improved interrupting performance and even further progress in the circuit breaker art may be confidently expected.

The authors wish to express their appreciation of the advice and assistance given them by Mr. J. B. MacNeill and Mr. H. M. Wilcox.

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Discussion

For discussion of this paper see page 191.

Extinction of A-C. Arcs in Turbulent Gases

BY T. E. BROWNE, JR.*

Associate, A.I.E.E.

Synopsis.—A recent theory of a-c. arc extinction in gas-blast circuit interrupters is reviewed. It is predicted on the basis of this theory that the interrupting ability of an a-c. arc should increase very considerably with the degree of turbulence to which the arc gases are subjected, and also that the recovery of dielectric strength by a turbulent arc space during a period of zero current should be very rapid for the first few microseconds and then comparatively slow for a considerable time thereafter. Experimental results obtained with an arc in atmospheres of various common gases verify these predictions, and also reveal the importance of the gas medium.

A curve has also been obtained showing recovery of dielectric strength with time during the current zero period by an arc in an expulsion fuse tube. This curve has the characteristic shape predicted by the turbulence theory, thus proving the validity of the theory as applied to the behavior of a practical gas-blast device.

* * * * *

I. Introduction

Of the published theory relating to a-c. arc extinction, that which explains the behavior of short arcs, depending almost entirely upon phenomena taking place at, or very near, the surfaces of the electrodes, is far more complete and in better agreement with experiment than that relating to long arcs, whose behavior is affected very little by the phenomena occurring very close to the electrodes. The latter, however, are probably of much greater practical importance, since it is with such arcs that engineers must deal in most present-day types of circuit interrupters operating in a-c. circuits of more than a hundred or so volts. Most of the practical circuit interruption difficulties are due to the fact that ordinary unconfined arcs must be drawn out to prohibitive lengths to interrupt power circuits of the higher voltages now in use. Because of this fact, it has been necessary to modify the arc in some way so as to increase the voltage gradient at which it may be extinguished. The various methods by which such modification has been accomplished usually result in a blast of gas being directed into or through the arc stream, which is confined to a restricted space. In circuit breakers employing arcs submerged in liquids, such as oil, carbon tetrachloride, or water, the surrounding liquid surface serves both to restrict the arc space and to furnish the gas blast by its rapid decomposition under the influence of the high-temperature arc. The fiber tube of the common expulsion fuse acts in a similar manner. In liquid circuit breakers, additional surfaces, magnetic fields, gas chambers, hollow electrodes, and so on, may be used to increase the effectiveness of the interaction between arc and liquid. Recently use has also been made of blasts of air,[1–4] carbon dioxide[1a] and hydrogen[1,4,5] directed by mechanical means into suitably confined arc spaces from high-pressure storage tanks.

The great effectiveness of gas blasts in aiding a-c. arc extinction is thus a well established experimental fact, but, though a number of theories has been suggested, there has been presented so far very little definitely conclusive evidence of an experimental nature to indicate the actual mechanism of their action. It is the purpose of this paper to describe some recent experiments that have been and are being made in an effort to obtain such information.

II-A. Review of Theory

It is now well established that the extinction of an a-c. arc in any practical circuit interrupter occurs at a moment of zero current, and is the result of a sudden transition of the arc space from a conducting to an insulating state. Since, according to modern theory, electricity is conducted through a gas by the motion of positive and negative ions, it follows that loss of conductivity by a gas must be due to disappearance of the necessary ions. In fact, the various means used in practise to accomplish the extinction of an a-c. arc can generally be shown by sufficiently complete analysis to be means of accelerating the removal of ions from, or deionization of, the gaseous arc space. The time available for this deionization, between current zero and the appearance of full circuit voltage across the arc electrodes, has been shown[6,7,8] to vary from about ten microseconds to several hundred microseconds.

Of the various theories put forward to explain the effectiveness of different types of gas-blast circuit interrupters, that proposed by Slepian,[9] and further developed by Slepian and Denault[10] in connection with the expulsion fuse, seems to the author to be the most general in its applicability and to escape objections that apply to other theories. In it, the major deionizing effect of a gas blast is ascribed to "the high degree of turbulence it introduces into the bounded gas space prior to current zero,"[10] rather than to actual sweeping away of ions,[1] introduction of a non-gaseous insulating medium,[11] "loading" of ions,[3] cooling the arc,[5] and so on, as suggested by proponents of other theories. The action of this turbulence is pictured as causing non-uniformity of ionization of the arc space, so that many comparatively small regions, or "filaments," of highly ionized and conducting gas are interspersed with, or surrounded by, masses of very much less intensely

*Research Laboratory, Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

1-4. For references see end of paper.

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ionized gas, either freshly introduced, or deionized by recent contact with the bounding walls in the course of its turbulent motion. At current zero, when the generation of ions within the conducting regions is momentarily stopped, the dimensions of these regions are such that they very quickly lose their high density of ionization by diffusion into the adjacent non-conducting gas, resulting in a nearly uniform ion distribution having a very much smaller maximum density, and consequently requiring a very much higher breakdown gradient.[9]

II-B. Predictions of Theory

On the basis of this theory, then, the dielectric recovery of a turbulent arc space may be thought of as

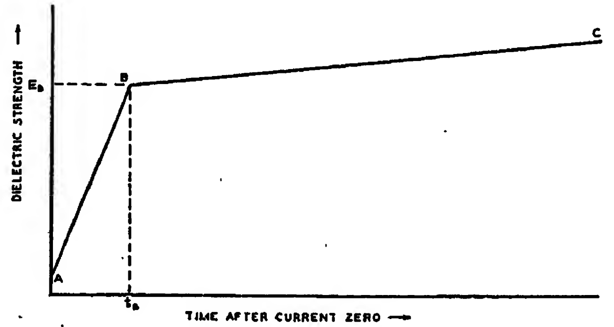

Fig. 1—Recovery of Dielectric Strength of Turbulent Arc Space, as Predicted by Theory

occurring in two stages. The first consists of a very fast rise resulting from the rapid diffusion of ions from the small filaments into the surrounding gas, and continues until a condition of approximately uniform ion density is reached. Following this is the second stage marked by a very much slower further recovery as ions are lost from the arc space by the means usually considered, such as diffusion to surrounding surfaces, recombination, "whisking away," and so forth. This is illustrated by the idealized curve *A B C* of Fig. 1, where *A B* represents the first stage and *B C* the second stage of the dielectric recovery. Since the slope of the line *A B* will depend upon the smallness of the conducting filaments at current zero, it follows that an increase in the turbulence of the arc space preceding current zero will result in an increase in this slope and a decrease in the time required to reach the uniform condition at *B*. For very small conducting regions such as may be expected with a high degree of turbulence, this time may be only a few microseconds. The effect of turbulence alone on the slower recovery *B C* is probably not nearly so great.

From these considerations, the effect of increasing turbulence on the interrupting ability of an arc in a circuit of given speed may be predicted. As long as the slope of *A B* is such that full circuit voltage is recovered in less than the time t_B, increasing the turbulence will yield a rapid increase in the volts-per-centimeter at which the arc will be extinguished. If t_B should become less than the circuit transient period, however, the improvement resulting from a further increase in turbulence would be only in proportion to the much smaller effect on the height of the line *B C*. This apparent maximum effect of turbulence should appear sooner with slow circuits and with arcs in rapidly diffusing gases, such as hydrogen. Of course, in practical gas-blast devices, the magnitude of the maximum short-time dielectric strength E_B and the time t_B required to reach it will also depend very largely upon conditions other than turbulence existing in the arc space prior to current zero. Such conditions, which govern the average density of ionization throughout the actual arc space at current zero and before, are current magnitude, proximity of confining walls,[6] rate of dilution by fresh gas, presence of solid or liquid bodies, or particles, within the arc space,[10] and composition of the arc gases.[4,5] In practise, of course, the volt-time recovery characteristic of the arc would hardly consist of straight lines and sharp angles, as in Fig. 1, but it may be expected to follow the general direction of these lines.

III-A. Experiments with Rotating Arc Structure

To test the validity of this theory, the arcing structure shown in Fig. 2 was used. In it, factors other than turbulence to which gas-blast effectiveness might be ascribed, such as the cooling, diluting, and scavenging

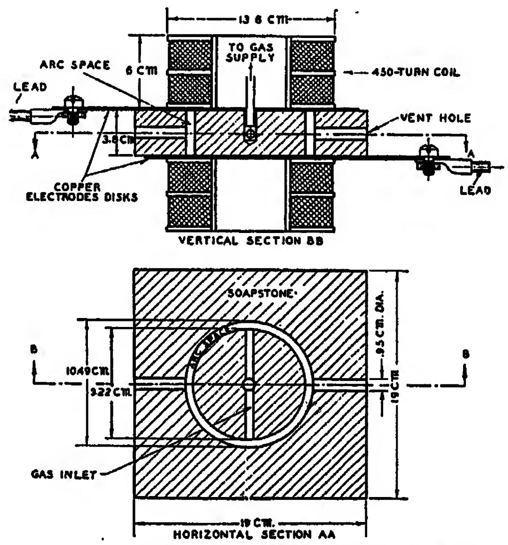

Fig. 2—Experimental Arcing Structure

effects of a high-velocity stream of fresh gas, were eliminated by dispensing with the gas blast, as such, and producing turbulence by driving the arc around the circular slot at high velocity by means of a strong radial magnetic field produced by passing direct current through the coils in such a direction that the radial components of their fields were additive in the region of the circular arc space. As illustrated, the apparatus was arranged so that the air in the slot could be replaced by other gases when desired. Ordinary commercial forms of oxygen, nitrogen, hydrogen, and carbon dioxide, as purchased in tanks, were used and a small flow of gas was maintained during the tests to prevent diffusion

of air back into the apparatus. The arc was initiated within the slot by the burning of a fine copper fuse threaded between the two copper-disk electrodes.

Fig. 3 gives the results of measurements, by means of probe electrodes and oscillograph, of the average speed of a 600-ampere, 60-cycle arc at different strengths of the driving magnetic field (produced by direct current) in the 0.635 cm. slot with atmospheres of oxygen, carbon dioxide, air and hydrogen. The speed for a given driving force seems to increase with decreasing density of the gas, if carbon dioxide is presumed to be almost entirely decomposed by the high arc temperature into carbon monoxide and oxygen. Fig. 4 shows similar results for a 1.9 cm. slot, obtained by reducing the diameter of the inner cylinder. The interchange of position, in this case, of the curves for carbon dioxide and for air is difficult to understand, and suggests that the process by which the arc moves through the gas under the influence of the magnetic field is not simple. The large

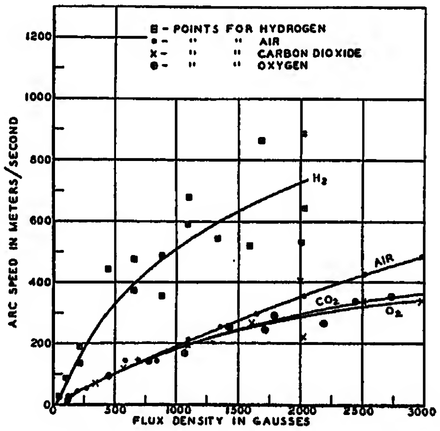

FIG. 3—AVERAGE SPEED OF A 600-AMPERE, 60-CYCLE ARC, 3.8 CM. LONG MOVING IN A CIRCULAR SOAPSTONE SLOT 0.635 CM. WIDE IN VARIOUS GASES AT ATMOSPHERIC PRESSURE, AS A FUNCTION OF AVERAGE RADIAL FLUX DENSITY IN THE SLOT. (D-C. FIELD)

variation shown by the scattering of the points, especially at the higher speeds, also suggests this. However, it is believed that, in general, the body of ionized conducting gas, or arc core, is driven against and through the surrounding non-conducting gas much as if it were an ordinary solid conductor, but having a less definitely marked bounding surface. The action of the moving arc on the rest of the gas in the slot is then similar to that of a leaky piston, driving all of the gas around the slot at a somewhat lower speed than that of the arc itself.

Fig. 5 shows that, with a constant field strength, increasing the arc current increases the speed of the arc according to a curve somewhat similar in shape to that of Fig. 3 with constant current. Detailed comparison of the two curves, however, shows that for the same values of βI, field strength times current, the smaller current arcs move considerably faster than do the higher current arcs. For example, at βI = 222,000 gauss-amperes, the 600-ampere arc moves at 76 meters per second and a 200-ampere arc at 90 meters per second. At 2,000,000 gauss-amperes, the 600-ampere arc is driven at 520 meters per second and an 1,800-ampere arc at only 355 meters per second. This seems to indi-

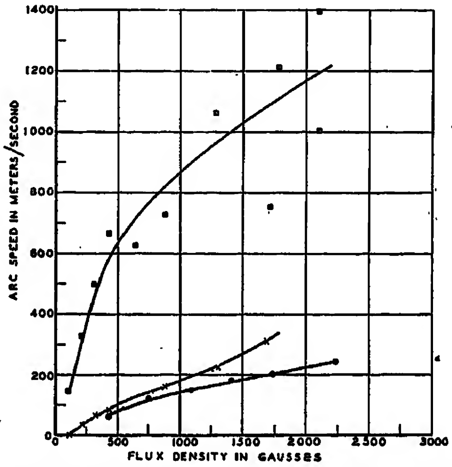

FIG. 4—AVERAGE SPEED OF A 600-AMPERE, 60-CYCLE ARC 3.8 CM. LONG MOVING IN A CIRCULAR SOAPSTONE SLOT 1.9 CM. WIDE IN VARIOUS GASES AT ATMOSPHERIC PRESSURE, AS A FUNCTION OF AVERAGE RADIAL FLUX DENSITY IN THE SLOT. (D-C. FIELD)

⊡ Points for hydrogen
× Points for carbon dioxide
● Points for air

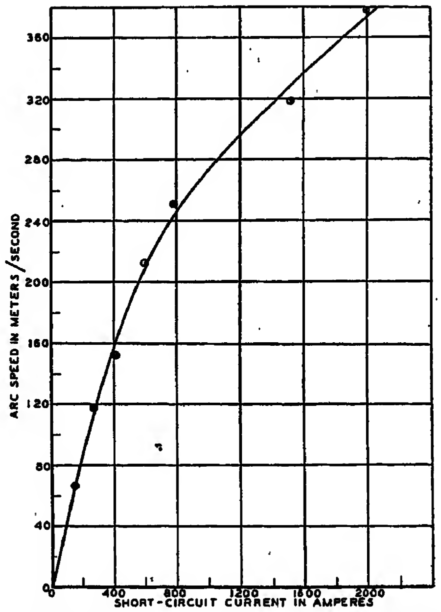

FIG. 5—CURVE SHOWING AVERAGE ARC SPEED IN AIR AT ATMOSPHERIC PRESSURE, AS A FUNCTION OF STEADY-STATE SHORT-CIRCUIT CURRENT (ARC CURRENT, APPROXIMATELY) FOR A 3.8-CM. ARC IN A 0.635-CM. CIRCULAR SOAPSTONE SLOT WITH AN AVERAGE RADIAL FLUX DENSITY OF 1,110 GAUSSES

cate the piston action of the arc, since the larger current arc may be expected to act as a more perfect piston and therefore be slowed up to a greater extent in moving the body of gas at a velocity nearer its own.

Of course, the effect, other than producing bodily motion, of the magnetic field upon the arc must be con-

sidered. Calculations, which had to be omitted for lack of space, were made on the basis of modern kinetic theory of gaseous conduction to determine the possible effect of the fields used in these experiments upon the mobilities and diffusion coefficients of ions and electrons in the arc space. These calculations show that this effect could be hardly any more than the imparting to the electrons of an additional transverse velocity, which, on being immediately transmitted by impact to the gas molecules, acted as a volume distributed force tending to move the arc as if it were a solid conductor. Additional evidence that the effects produced were due to the resulting velocity rather than to the magnetic field is given by the fact that an alternating field nearly in phase with the arc current produced almost as great an effect on the extinction at current zero, as the field due to a direct current of the same r.m.s. value. In the a-c.

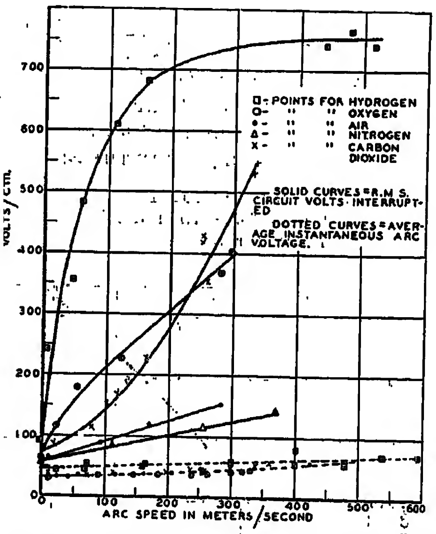

FIG. 6—INTERRUPTING ABILITY AND ARC VOLTAGE OF A 600-AMPERE, 60-CYCLE ARC, 3.8 CM. LONG AS A FUNCTION OF THE AVERAGE SPEED WITH WHICH IT IS DRIVEN AROUND A 0.635-CM. CIRCULAR SOAPSTONE SLOT BY A RADIAL D-C. FIELD IN VARIOUS GASES AT ATMOSPHERIC PRESSURE

field case, the flux density at the current zero of the arc was very slight, so that the change in the arc's extinction characteristics must have been due to a condition caused by the action of the field on the arc prior to current zero. It is believed that this condition was the turbulence of the arc gases resulting from the arc's velocity, which was, in turn, produced by the force due to the transverse magnetic field.

The power supply for these experiments consisted of two 50-kva. transformers with 2,300-volt, 60-cycle primaries arranged to provide a considerable number of secondary voltages. The current was limited almost entirely by large air-core station-type reactors, having very low resistance and distributed capacitance. The time required for full circuit voltage to appear across the arc after current zero is estimated to be of the order of ten microseconds for a circuit of this type. For the sake of uniformity of conditions, the reactance of the circuit was adjusted so as to obtain a short-circuit current of approximately 600 r.m.s. amperes in all of the experiments for which results are presented. The circuit was closed by means of a synchronously controlled short-circuiting switch, to obtain symmetrical first cycles. At each of a series of circuit voltages, the current in the field coils was adjusted by repeated trial to the minimum value that would just cause extinction of the arc after not more than two half-cycles. The results of a series of such experiments with arcs in the 0.635 cm. slot in atmospheres of air, nitrogen, carbon dioxide, oxygen, and hydrogen are shown in Fig. 6. The r.m.s. circuit voltage at which the arc was extinguished is plotted against the arc speed which corresponds to the critical field current, as shown by Fig. 3. The arc-speed *vs.* field-strength curve in nitrogen was assumed to be the same as that in air. Values of average arc voltage are also plotted in this figure.

These curves show very clearly that increasing the turbulence of the arc gases does increase the dielectric strength recovered by the arc space within a given short time after current zero. The arc voltage was also increased, but not to so great an extent. This probably indicates that the rate of formation of ions in the arc increases more rapidly than the first power of the arc voltage. Thus, at the highest arc speeds, the increase in rate of ion production due to an increase of 100 per cent or less in arc voltage during the half-cycle would be sufficient to balance the greatly increased rate of loss of ions which causes a dielectric recovery of several hundred per cent during the current zero period; and this is seen to be the case.

One very interesting fact strikingly revealed by these curves is the great difference between the interrupting ability of arcs in different gases for the same arc velocity. The superiority of hydrogen as an arc atmosphere is not surprising, because of the smaller mass and resulting higher rate of diffusion of the hydrogen ions, but the great difference between oxygen and nitrogen is not predictable from their molecular weights. The curve for air, which is largely nitrogen, lies closer to the curve for nitrogen than to that for oxygen, as might be expected. No reason is definitely known for the apparent slow deionization of the turbulent arc in nitrogen. It might be due to the formation of relatively massive, slow diffusing "clusters"[12] of molecules about positive ions, or to some other property or process of similar or different character. The peculiar upward bending of the carbon dioxide curve is difficult to explain, but the general agreement in magnitude of this curve with that for oxygen would seem to follow from the assumption that the gas at arc temperatures is largely a mixture of oxygen and carbon monoxide, which latter has a molecular weight comparable with that of oxygen. The flattening of the hydrogen curve at the higher velocities seems to indicate the approach to a maximum effect of turbulence as predicted in the theory.

In Fig. 7 are plotted a few similar data obtained with a slot three times as wide, for comparison with those of Fig. 6. The line for air, located by two points, has practically the same slope as the corresponding straight line for air in the narrower slot. The difference in the behavior of the arc in carbon dioxide in the two cases is very surprising, however, and seems to defy explanation.

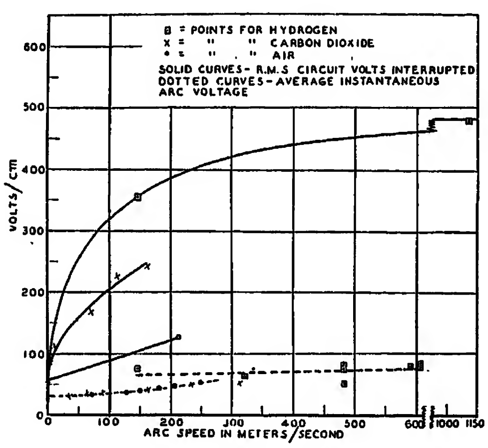

Fig. 7—Interrupting Ability and Arc Voltage of a 600-Ampere, 60-Cycle Arc, 3.8 Cm. Long, as a Function of the Average Speed with which is Driven Around a 1.9-Cm. Circular Soapstone Slot by a Radial D-C. Field in Various Gases at Atmospheric Pressure

At the lower velocities the wider slot is superior to the narrower, but as the arc speed is increased the curve flattens out rapidly. With a gradient of only 350 r.m.s. volts per centimeter, the arc showed no tendency to go out at the highest speeds obtainable with the apparatus. Somewhat similar inconsistencies between the arc speeds in carbon dioxide for the same field in the two slots may be noticed in Figs. 3 and 4. Thus, it seems that there must be processes taking place in the carbon dioxide arc which do not occur with simpler gases. These may be related to the chemical decomposition of carbon dioxide mentioned above. The lower values of volts-per-centimeter interrupted by the arc in hydrogen for the same speeds, and especially the lower value at which flattening apparently occurs, seems to indicate the effect of proximity of the bounding walls on average ionization density at current zero, mentioned in the above discussion of theory.

In Fig. 8 is shown the result of a series of experiments to determine the manner of recovery of dielectric strength with time after current zero for a turbulent arc. The arc, of 600 amperes as before, was driven around the 1.9 cm. slot in carbon dioxide at an average speed of 68 meters per second by a d-c. field of 342 gausses. The rate of recovery of voltage across the arc electrodes was controlled and measured by means of resistance shunts, which were adjusted by trial at each of a series of voltages to the maximum value at which the arc would just be extinguished at the first current zero, which was made to occur at peak generated voltage. The exponential voltage rise curves corresponding to these critical values are plotted in the figure. The solid curves were calculated from the circuit constants, neglecting distributed capacitance and assuming that the voltage started from zero instead of negative arc voltage. The dotted curve was plotted from an actual oscillogram taken at the critical conditions for the highest voltage used. The envelope of this system of curves must represent the instantaneous dielectric strength of the arc space at any time after current zero. Of course, the envelope obtained in this manner cannot be extended all the way to zero time, since the effect of the unknown distributed capacitances of the circuit becomes appreciable for the high-speed transients, preventing accurate plotting of voltage rise curves reaching their peak in times of the order of ten microseconds, the estimated recovery period of the circuit when unshunted. This curve does show, however, that the turbulent arc space regains the ability to withstand a considerable voltage gradient within a time which is less than that permitted by most practical circuits in which circuit interrupters are required to operate. It also shows that further increase of dielectric strength following the initial very rapid recovery is comparatively slow. This behavior is exactly that which would be predicted from Slepian's theory of the deionization at current zero of a long a-c. arc subjected to turbulent gas flow, as illustrated by Fig. 1.

III-B. Experiments with an Expulsion Fuse

Since the experiments described above were all made with an artificial arcing structure, it seemed very

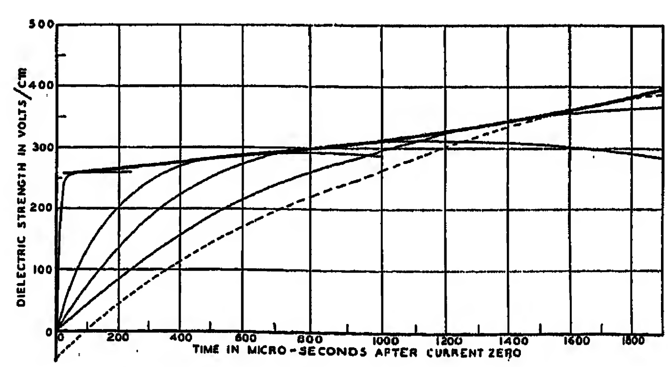

Fig. 8—Recovery of Dielectric Strength with Time Following the First Current Zero of a 600-Ampere Arc in a 1.9-Cm. Circular Soapstone Slot 3.8 Cm. Long, Containing Carbon Dioxide at Atmospheric Pressure, the Arc being Driven at an Average Speed of 68 Meters per Second by a Radial D-C. Field of 340 Gausses

desirable to study also the extinction characteristics of a practical gas-blast device in order to prove or disprove, if possible, the validity of the turbulence theory as applied to it. For this study, an expulsion fuse, consisting of a fiber tube 1.6 cm. in inside diameter and 7.6 cm. long, was employed. The tube was closed at one end and vented at the other through a hollow electrode. The power was supplied in these tests through a bank of six

333-kva., 23,000 to 2,300 or 1,150-volt transformers, used in series and parallel combinations to obtain various secondary voltages. As before, the current was limited principally by air-core reactance, 400 amperes (symmetrical short-circuit value) being used in this case. By the same method as that employed in obtaining the data of Fig. 8, an envelope representing the recovery of dielectric strength with time after current zero was obtained for the fiber fuse. This is shown in Fig. 9, with the curve of Fig. 8 repeated for direct comparison. Although the expulsion fuse curve is not quite so flat, its general similarity in shape to the upper curve obtained with the experimental turbulent arc device is evident. The greater slope of the expulsion fuse curve for the first few hundred microseconds after current zero may be due to the diluting effect of a continued injection of fresh gas from the still decomposing fiber walls. The high pressure initially existing within the tube will also result in a continuation of the gas-blast

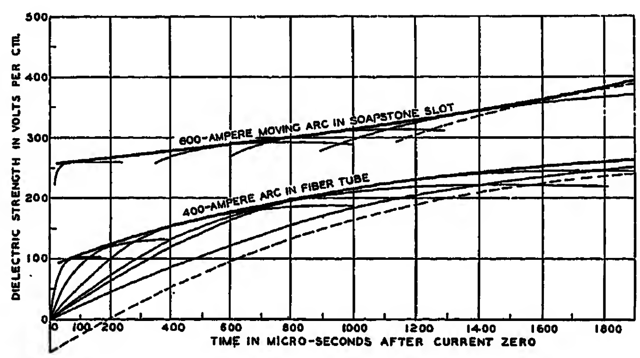

Fig. 9—Recovery of Dielectric Strength with Time Following the First Current Zero of a 400-Ampere Arc in a 1.6-Cm. Fiber Tube, 7.6 Cm. Long, Compared with a Similar Curve for a Turbulent Arc in a 1.9-Cm. Soapstone Slot in Carbon Dioxide

after gas generation has ceased, thus continuing the scavenging, or sweeping away action. Of course, neither of these conditions can exist to an appreciable extent in the soapstone slot device.

Because of the different conditions in the two cases, it may not be strictly permissible to make quantitative comparisons based on these curves, but the result of an attempt to do this may be of some interest. Calculations, again omitted for lack of space, indicate that the velocity of the gas in the fuse tube is of the same order of magnitude as that in the soapstone slot. The average arc-voltage gradients during the half-cycles were about the same. In the rotating arc case the gas may be considered to be practically an equal mixture of carbon monoxide and oxygen. The gases generated in the fiber fuse, on the other hand, have been shown[10] to be an approximately equal mixture of carbon monoxide and hydrogen. In the latter case, however, it seems probable that there may have been an appreciable quantity of nitrogen-containing air remaining in the tube at the first current zero to counterbalance the favorable effect of the hydrogen. In justice to the fiber-tube expulsion fuse, it should be explained that the current chosen for these tests is that which gives the lowest voltage interrupting capacity[10] with a tube of this size.

IV. Conclusions

The results of these experiments reveal the following facts:

1. That, in general, the interrupting ability of an a-c. arc is greatly improved by turbulent motion of the arc gases, this improvement increasing, in a fast circuit, almost in direct proportion to the gas velocity from which the turbulence results.

2. That the interrupting ability of a turbulent a-c. arc depends very largely upon the composition of the arc gases, most gases being decidedly superior to air in this respect.

3. That the recovery of dielectric strength following a current zero by an a-c. arc subjected to turbulence takes place in two consecutive phases, the first consisting of a very rapid recovery to a substantial value in a few microseconds, and the second of a very much slower further recovery for a much longer period, and

4. That at least one practical gas-blast circuit interrupter, the expulsion fuse, exhibits a volt-time interruption characteristic which clearly indicates the role of gas turbulence in its operation.

Conclusions (1), (3) and (4) are entirely in accord with the predictions of the theory proposed by Slepian and Denault,[9,10] and are believed to constitute convincing proof of the essential correctness of this theory. Conclusion (2), which lacks definite theoretical explanation, disagrees with the observations of some experimenters,[4,5] and agrees with those of others,[1a] but the experimental fact is well verified, and helps to explain the success of many enclosed-arc circuit interrupters. It is hoped that further results, similar to those from which conclusion (4) was drawn, may be obtained for arcs in other types of gas-blast interrupters. For the oil circuit breaker, which is probably the most important of such devices, some interesting experimental information recorded by Park and Skeats[7]* appears to indicate a volt-time recovery curve which is similar in shape to those given in the present paper. These results were obtained with an ordinary plain-break circuit breaker. Additional results presented by Prince and Skeats[11]† for an explosion pot type of oil breaker, with and without special contacts, seem to indicate similar characteristics, in spite of claims made for an entirely different method of arc extinction in these cases. Further and more systematic investigation of the volt-time dielectric recovery characteristics of arcs in oil circuit breakers, and in other types of gas-blast devices as well, would seem to be very desirable. Also, an accurate determi-

*Fig. 14 and accompanying text of their paper.

†Curves of Fig. 11 on page 511.

nation of such curves for times of the order of ten microseconds and less after current zero would be of considerable interest from the standpoint of theory.

V. Acknowledgment

Much of the credit for this work is due Dr. J. Slepian, who suggested and guided it. The expulsion fuse experiments were conducted by Mr. G. S. Rowley.

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Discussion

THE THEORY OF OIL-BLAST CIRCUIT BREAKERS
(Prince)

PRACTICAL APPLICATION OF THE OIL-BLAST PRINCIPAL OF CIRCUIT INTERRUPTION
(Spurck)

RECENT DEVELOPMENTS IN ARC RUPTURING DEVICES
(Van Sickle and Leeds)

EXTINCTION OF A-C. ARCS IN TURBULENT GASES
(Browne, Jr.)

Philip Sporn: I would like to stress a point that I laid before the Institute a year ago, and that is the question of the standard duty cycle on breakers. The electrical industry is today paying a heavy penalty because of the continuation of the present totally inadequate and in many cases disregarded OCO 2-minute OCO standard cycle. We found, for example, only a month or so ago that one of our own companies was making it a standard practise to open up every breaker on its system above a certain voltage rating after it had interrupted an arc twice under short circuit and this was regardless of whether the guarantee of the breaker was well above the duty that was being imposed upon it. Such practises are bound to exist in many other companies and are costing the industry thousands of dollars every year. In the light of the data as to the successful performance under repeated short-circuit cycles developed during the Philo 1930 tests and also in view of the data developed in the present papers by Messrs. Van Sickle and Leeds and by Mr. Spurck, isn't it high time for the progressive oil switch manufacturers to offer the users of oil circuit breakers a duty cycle that is more consistent with actual and economical power system operation, and that would not at the same time stress the modern designs to anywhere near their limits?

C. L. Fortescue: Some years ago it was felt that circuit breakers using the old method of rupturing arcs had reached the limit of their capacity. We then undertook a fundamental research on the characteristics of long arcs with a view to finding out how they were formed and how they could be quenched. Dr. Slepian was assigned to this research work and the deion circuit breaker and the deion grid oil circuit breaker are part of the results of his investigations.

Some years ago I had the idea that by stabilizing an a-c. arc through a long path it would go out of itself at zero current so I made up two cylindrical choke coils of large diameter and spaced them apart on the same axis leaving a small space between them for the arc chute protecting the choke coil from the arc by thick plates of asbestos board. The choke coils were arranged so that the arc itself formed the series connection between the two choke coils, one terminal of one choke coil was arranged for connection to an 11,000-volt trolley and the other terminal connected to ground and the arc started by connecting together, with fuse wire, the other two terminals which consisted of two small horns and the circuit was closed between the terminal of one choke coil and the trolley. The arc was then established and as expected it stabilized between the two choke coils in the form of a ring but much to my surprise it did not go out at zero current as I expected. The frequency of the alternating current was 25 cycles so that the condition was favorable to deionization of the long arc. As I recall, the mean diameter of the two coils was about three feet so that the length of the arc must have been about nine and one-half feet. This indicated to me that something besides length in the arc was required to quench it and this requirement is, as Messrs. Browne, Van Sickle and Leeds show, a turbulent gas stream across the path of the arc which was not present in the test.

Mr. Prince mentions washing away the products of the arc and in other places he seems to have the idea of interposing a solid layer of oil between the arcing electrodes. He presents test data to support this point of view, but is not this data just as well explained by the fact that the gas formation and its turbulence is a function of the velocity by which the oil is introduced into the ionized path between electrodes? It would seem to me that until the current had approached quite near the zero point any oil directed against the arc stream would be volatilized even at the high pressures produced in the arc chamber. Therefore, the time left to establish the solid oil barrier would probably not exceed 20 or 30 microseconds and this solid barrier even at a velocity of 130 ft. per sec., as indicated in Mr. Prince's paper, would not progress more than 0.04 inch, or taking a value of 100 microseconds, which is believed to be liberal, the solid barrier of oil would not have advanced more than 0.134 inch. It is hard to see where this can be considered as washing away the products of the arc.

In the theory advanced by Dr. Slepian the action suggested appeared to be reasonable and we know that arc quenching, as it takes place in expulsion fuses and the Torok tube, must take place in some such manner as explained in Dr. Slepian's theory. Why, therefore, invent a different answer for a different type of mechanism? Is it not more reasonable to suppose the quenching of the arc takes place in the same way in all cases?

Mr. Browne, I feel, has made tests which support Dr. Slepian's theory very strongly and the successful operation of the deion grid, as pointed out in the paper by Messrs. Van Sickle and Leeds, in which the action could not be due to interposing a layer of cold oil between the electrodes, further supports this theory.

Reverting to lightning phenomena, one reason that I have put forward for the fact that the lightning currents do not reach values high enough to produce serious induced surges is the nature of the cloud atmosphere and the difficulty of producing ionization therein. Now it is known that the cloud atmosphere is in a high degree of turbulence and this, by still further increas-

ing the difficulty of ionization, may be a contributing factor in restricting the rate of discharge of the thundercloud.

In the case of the oil breaker no doubt free electrons are present in large quantities in the arc stream and the idea of washing away the electrons seems to me to be impractical.

J. B. MacNeill: It seems safe to predict that in the future circuit breakers need not be a limitation of system or station development in the way that they were several years ago. Other limitations to the capacity concentrated on short circuit at a given point must be considered. The general problem before the industry of which circuit breaker operation is but one part, is that of overall protective system operation. For some time it has been realized that the accumulation of time increments on large systems to secure selective relay action, provided only inadequate protection. The paper by Goldsborough and Lewis is the result of a scientific study of the factors available for selective action, and outlines ingenious methods of suiting apparatus to the requirements. This paper records a noteworthy contribution to the high speed relay art for all lengths of lines and with dependable high speed operation.

It would appear that the oil blast device given in the papers by Messrs. Prince and Spurck, operating as it does on one end of the arc, would be most effective for low voltages. However, for high voltages in which relatively long arcs are obtained, one questions the ability of a device operating only on the upper arc end to exert sufficient effect on the arc as a whole, to produce effective results. On the other hand, a device such as the deion grid interposing successive increments of arc rupturing ability as the arc lengthens, in which the gas formed passes transversely across the full arc length, impresses one as being better fitted for high-voltage circuits.

If reference is made to Fig. 9 of Mr. T. E. Browne's paper, there will be seen the almost instantaneous restoration of dielectric strength in devices of the turbulent gas type. The speed of oscillation of a high-voltage transformer without shunting lines is usually less than 10,000 cycles per second. Such a circuit obtains full voltage (¼ cycle) in 25 microseconds. Even in this short time the turbulent gas device has reached the knee of the curve. A 132,000-volt transformer circuit connected to an alternator is shown in Fig. 3 of the paper by Messrs. Van Sickle and Leeds, and shows approximately 4,300 cycles per second. Approximately 60 microseconds are required for ¼ cycle of this circuit. The advantage of rupturing devices such as deion grids operating under this principle, is obvious, especially for high-voltage work, over devices which build up dielectric strength only in a straight line relation to time for a considerable period.

T. E. Browne, Jr.: In the paper presented by Messrs. Van Sickle and Leeds, one of the most interesting facts from the standpoint of fundamental theory is that revealed by comparison of the curves showing reduction of arc energy with those showing the corresponding reduction in arcing time. As stated by the authors, the smaller arc energy with deion grids as compared with plain breaks results from an *actual reduction in arc voltage* as well as from the reduction in time duration of the arc. This is brought out most forcefully in the case of the lower-voltage power-house breakers, where, for example, Fig. 14 shows that at 30,000 amperes the application of deion grids effected a reduction in arc energy of approximately 50 per cent, while the corresponding reduction in arcing time, as shown by Fig. 13, is roughly only 20 per cent. The 30 per cent discrepancy obviously must be due to reduction in arc voltage resulting from diminished total length of the arc when controlled by the grids. In spite of this reduction in overall length and voltage, the shorter arc, since it is subjected to a so much more effective turbulent gas blast, is able to interrupt the circuit at current zero just as certainly as is the longer less-efficient unconfined arc.

This is further practical evidence of the fact, brought out by the experiments described in my paper, that the effect of turbulent gas flow on a confined arc is to cause it to approach very close to the ideal a-c. circuit interrupting agent, which, as pointed out by Dr. Slepian and others, should be able to carry the current with negligible power loss during the half-cycle and then change over instantly at a normal current zero from a good conductor to an adequate insulator. It is noteworthy that these desirable characteristics are almost completely attained in the gaseous arc space of the deion grids by gas-blast action alone.

The oil-blast theory of circuit interruption, presented by Mr. Prince, has been of great interest to me since it was first proposed a year ago. After carefully studying the exposition of the theory and the supporting evidence presented at that time and added to at frequent intervals since, as well as the present paper, I find it, however, quite impossible to agree with Mr. Prince's conclusion that the theory is "unquestionably" valid, either for the so-called impulse type, or any other existing kind of breaker. For example, all of the data presented in this paper appear to me to be either inconclusive or actually at variance with the oil-blast theory. In Fig. 1, as a first instance, it is shown that the impulse strength of good and of poor oil approaches equality only for times of the order of one microsecond or less, and that for a surge period of 100 microseconds or more, shown to exist in all practical high-voltage circuits so far investigated, the difference becomes of the order of two and one-half to one, which it would seem ought to make itself apparent in any careful series of tests if the behavior of the breaker actually does depend directly and quantitatively upon the dielectric strength of liquid oil, as stated. If, however, the action of the breaker should depend upon the dielectric strength of gases resulting from decomposition of oil, it is clear that the lack of relation between oil quality and breaker performance actually observed is entirely plausible.

In the case of Fig. 2, showing rate of rise of circuit voltage as a function of necessary oil velocity, it is difficult to understand why, on the basis of the data, that the curve separating the points representing failures from those representing successful operations should have been drawn as a straight line through the origin. Although the wide scattering of the failure points would make the definite location of any curve drawn as a boundary to them doubtful, a curve that is concave upward and passes through the Y axis of zero oil velocity at a recovery rate of about 150 volts per microsecond would seem to fit the cross-marked points much more closely. This critical rate of rise of voltage of 150 per microsecond is no doubt about right for the plain-break oil circuit breaker, which Mr. Prince's impulse breaker would be at zero oil velocity. It is exceedingly common knowledge that a plain-break oil breaker is, and has always been, able to interrupt high-voltage circuits having rates of voltage rise which are certainly far in excess of zero. Conceding, however, that there is indicated a certain amount of general correlation between critical circuit speed and oil velocity, it still remains true that such correlation is to be expected on the basis of either a "solid" oil or a gas-blast theory, since the constriction of the arc and the intensity of the gas blast must also increase with the increasing oil velocity, making this figure of little value in comparing the two theories.

In Figs. 3 and 4, where the same data used in Fig. 2 are replotted with voltage and current as respective ordinates, it is also difficult to understand why any existing correlation between these quantities and oil velocity should be expected to show itself, in view of the wide range of circuit speeds represented, after circuit speed had just been shown in Fig. 2 to be a controlling factor. Even so, the difference between these two figures, in which lines are omitted, and Fig. 2 in which the line is drawn, is not impressive. In any case, would it not be necessary, in order to prove or disprove correlation between any one of the three variables (current, voltage and circuit speed) and oil velocity, to hold the other two variables constant?

With regard to Fig. 7, where rate of voltage rise is plotted against oil pressure in an explosion pot, the same general comments made in Fig. 2 may be repeated, including the observa-

tion that a certain degree of correlation is to be expected on the basis of either an oil-blast or a gas-blast theory.

The moving-picture photographs reproduced in Fig. 8 from an earlier article, and taken, as Mr. Prince says, "in an attempt to satisfy *pardonable* skepticism," seem to me to have just as much, or as little, to do with the fundamental question of what happens at current zero, as do previous much clearer diagrams of events taking place at these other less important moments. I do not believe that the eventual replacement of arc gases by liquid oil *after* extinction of the arc in any oil circuit breaker has ever been seriously questioned. The question is: "How soon after?"

In summing up this so-called "relevant" information on which his conclusion is based, it seems to me that Mr. Prince has overlooked some data which are far more relevant than any presented in his current paper. These are the data of Fig. 11 in the oil-blast paper by Messrs. Prince and Skeats presented last year. In this figure the results of field tests on a 132,000-volt, 600-ampere explosion-pot breaker, both with and without oil-blast contacts, were presented in terms of inches of arc required to interrupt the circuit as a function of calculated circuit recovery time. In order to reduce these curves to the more fundamental form of interrupted-voltage gradient, or average dielectric strength of the arc, against time, they have been replotted in the accompanying Fig. 1 with ordinates equal to the circuit voltage divided by the original ordinates (inches of arc), giving the effective dielectric strength of the arc space after current zero in volts per inch. The similarity between these curves and corresponding curves

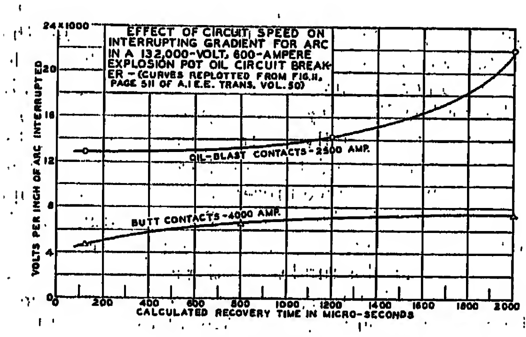

Fig. 1

for two admittedly gas-blast devices, as shown in Figs. 8 and 9 of my paper, is immediately evident. Study of similar data presented two years ago by Messrs. Park and Skeats reveals the demonstration of generally similar characteristics for another explosion-pot breaker and for a plain-break oil circuit breaker as well. Specifically, I should like to ask Mr. Prince why, if his hypothetical constantly-growing oil film is able to attain a thickness sufficient to produce the dielectric strength indicated for the oil-blast contacts in the extremely short time of 60 microseconds, that it does not continue to grow at at least this rate so as to obtain a further gain in effective dielectric strength of the order of 30,000 per cent after 2,000 microseconds, nearly one-eighth of a cycle later, instead of the mere 75 per cent increase actually observed?

In conclusion, I should like respectfully to submit three general reasons why it is impossible for me to agree with Mr. Prince's conclusions:

1. As pointed out repeatedly by Dr. Slepian, no detailed picture, capable of surviving critical analysis, of the mechanics by which his oil-film may be formed has yet been presented or discovered.

2. All of the data so far presented in support of the oil-blast theory seem to be preponderantly in favor, rather, of the gas-blast theory.

3. That the oil-film hypothesis is quite unnecessary, since it has been proven by laboratory results and by practical demonstration with deion grids as well, that the properties of a turbulent arc, such as is bound to exist in the oil-blast circuit breaker, are adequate to explain the breaker's behavior.

R. C. Van Sickle and W. M. Leeds: The realization that the gases produced in an oil circuit breaker, formerly considered merely a necessary evil, may actually be utilized to great advantage in the extinction of a-c. arcs, has brought about radical changes in circuit breaker construction. Mr. Browne has shown in his paper that the interrupting ability of a circuit breaking device is dependent among other things on two factors: first, the degree of turbulence of the arc gases, and second, the particular composition of these gases. In the deion grid construction, a very high degree of turbulence is obtained by drawing the arc in a narrow slot and directing the gases as a horizontal blast through the arc stream. If it were necessary to sweep the ionized gas particles a distance of several inches to prevent reignition of the arc at a current zero, a tremendous velocity would be required to accomplish this in the few microseconds available. However, Mr. Browne has brought out the fact that the turbulent condition of the arc just previous to a current zero is responsible for an extremely high initial rate of recovery of dielectric strength. When interrupting circuits with unusually fast-rising recovery voltages, this phase of the extinction process apparently determines whether the arc will be reestablished or not, and the complete removal of ionized particles by the motion of gas or oil volumes becomes a matter of secondary importance.

The gases produced by the decomposition of circuit breaker oil during the arc rupturing process have been analyzed by many investigators and found to contain approximately 70 per cent hydrogen. In view of the marked superiority in interrupting ability shown by hydrogen over air and other gases used in Browne's experiments, it is evident that the use of oil in an arc rupturing device, in addition to advantages of insulation and cooling, provides a supply of gas which as an extinguishing medium is much better than other common gases.

In comparing the results obtained with Mr. Browne's experimental structure and with deion grids certain differences in the functioning of the two devices should be pointed out. In Mr. Browne's device, the arc is driven around a circular path at high velocity by magnetic means so that the arc passes a given point in the gas many times at very short time intervals during which the gas does not have time to become completely deionized. The successive passages of the arc build up a state of moderate ionization in the gas. However, in the deion grid, relative motion is produced by holding the arc more or less stationary and directing a rapid turbulent flow of gas transversely through it. This gas is produced from the decomposition of the oil adjacent the arc and is initially un-ionized. Furthermore, after passing through the arc stream, this gas is discharged from the grid and not used again. It is thus evident that the rate of rise of recovery of dielectric strength is more rapid in both the initial and later stages, due to the lower density of ionization in the space surrounding the arc as the current approaches zero and to the dilution by fresh un-ionized gas after zero.

These differences may explain why the recovery voltage gradients of deion grids are higher than those obtained by Mr. Browne on his experimental device.

J. Slepian: Two years ago, in the closing discussion on my paper, "Extinction of Long A-C. Arcs," Trans. A.I.E.E. V. 49, p. 445, 1930, in commenting upon the suggestion of Mr. Prince that circuits might be interrupted by "whisking the arc products away," I found it necessary to point out that contrary to general impression, the arc in circuit interrupters performs necessary and useful functions and that "whisking it away," if it were really accomplished, would have serious and unpleasant consequences, unless other means were provided to take over the functions normally exercised by the arc. It seems necessary to expound briefly upon this point again, since the significance of this matter does not seem to have been grasped by the proponents of the oil film theory of operation of practical oil circuit breakers.

The useful function of the arc may be seen by considering what would happen if an arc did not form spontaneously upon separating a pair of contacts in a power circuit. If the arc did not form, then at the moment of separation of the contacts the current would necessarily at once drop to zero. Such an instantaneous reduction of the current to zero would induce disastrously high voltages in the circuit. But it may be suggested, why not separate the contacts at a moment of current zero when no high voltages will be induced? This would be an excellent suggestion if the electromechanical problem of synchronizing the separation of the contacts with the current zero was not so extraordinarily difficult to solve. Consider the complicated and variable relations which govern the moment of reaching the current zero in a circuit, and which would make it impossible to start going the contact separating mechanism much ahead of the current zero. Consider the enormous force necessary to accelerate and get going the contact separating mechanism in so short a time. Consider the difficulty of controlling this force so exactly as to synchronize with a normal current zero within a few microseconds. Remember that when dealing with such short time phenomena bars, ordinarily thought of as rigid, are annoyingly flexible, and fluids such as oil are highly compressible.

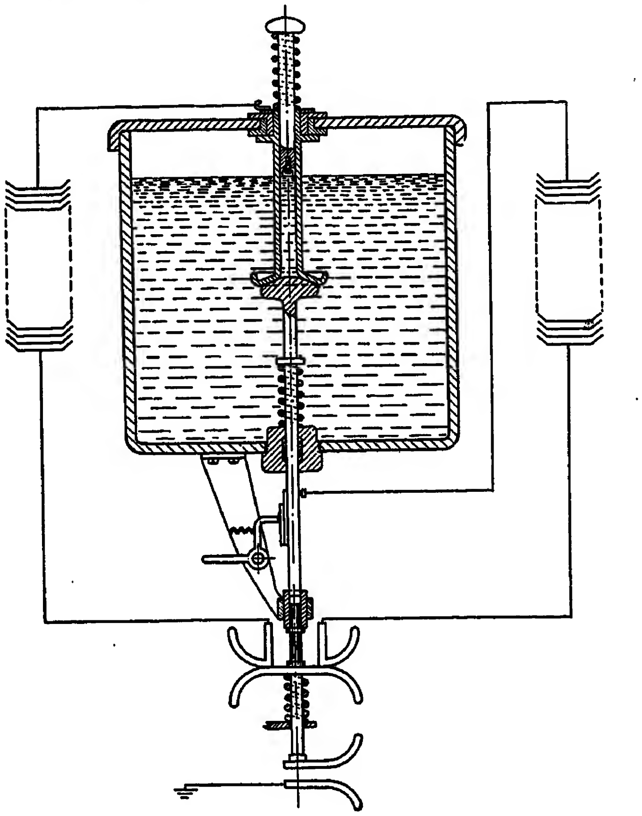

Fig. 2—L. W. Chubb Circuit Interrupter

(U. S. Patent No. 12,36,674)

The arc relieves us of these difficulties. We separate the contacts when we please and the arc permits the current to continue to flow so that no high voltages are induced. Then, of itself, in a well designed switch of course, the arc seizes upon a moment of current zero for changing from conductor to insulator, thus opening the circuit without the induction of high voltage. Thus no mechanical synchronization with current zero is required. The arc of itself performs this synchronizing function for us so that circuit breakers using arcs are in practical operation everywhere without causing damage to other electrical apparatus.

The problem of improving circuit interrupters is not one of getting rid of, annihilating or "whisking away" arcs, but of using arcs more efficiently and particularly using more effectively the inherent capacity of the arc for interrupting circuits synchronously with a normal current zero. Mr. Prince, who separates his contacts at a random time, admittedly uses an arc up to a moment of current zero, but just at the moment when the arc is ready to work for him and interrupt the circuit, he aspires to drive the arc away and interpose a growing film of oil between the contacts. However, and fortunately, the means he uses are inadequate to form such an oil barrier at any time, let alone synchronously with current zero, so that even in his breakers the arc interrupts the circuit.

It is possible to intensify the mechanical means which Mr. Prince uses so that they will cause a barrier of oil to be interposed between the separating contacts and interrupt the arc but the mere intensification of these means cannot cause them to form a barrier at current zero, and refrain from forming it at any other time. Fig. 2 in this discussion shows a circuit breaker made and tested many years ago by W. L. Chubb, which used means similar to those proposed by Prince. The actuating means, however, which was a sledge hammer blow upon the small piston, was so much more powerful and effective that an oil film really was interposed between the electrodes, squeezing out the arc. But as the lightning arresters indicated in the figure show, high voltages were expected and were obtained since there was no synchronization of the formation of the oil barrier with a normal current zero.

The discussion of Mr. Prince's paper is made difficult because results, even those which he states are the most convincing, are given without supporting data, but references are given to brief articles in other journals. Looking these up, we find that sufficient description of his test methods and methods of calculation are not given to permit any critical estimate of their validity, and there is the further difficulty that frequently reports of results of the same tests are mutually contradictory. But waiving these objections, when subjected to a moderately careful inspection, the results which Mr. Prince presents wholly fail to support any of the conclusions which he draws. The following criticisms are numbered so that none may be inadvertently overlooked.

1. Although it is the fundamental problem of the oil blast theory, neither in this paper, nor in the paper of last year is any detailed attention given to the hydro-mechanical problem of synchronous formation of the growing "solid oil" barrier. Nowhere in the present paper is it stated just where in the oil the velocity occurs which is used as the abscissas of Figs. 2, 3 and 4, although in the next to the last paragraph of the paper it is stated that these curves are the most convincing evidence which the author offers.

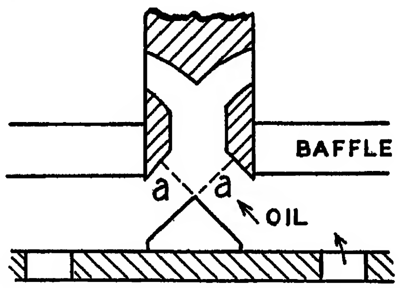

Fig. 3—Oil Boundary at Time of Interruption

1a. In the reference No. 2 which Mr. Prince cites and from which the data for these figures are taken, a diagram is shown, reproduced here as Fig. 3, in which it is suggested that the velocity in question is the mean velocity over a section of the passage leading up to the arc. The velocity is calculated from the motion of the piston without considering the influence of the compressibility of the oil which must be an important factor when the free surfaces *a-a* are so violently accelerated.

1b. The obstructing film is said to form by the uniform motion of the free surfaces *a-a* with the calculated velocity used in Figs. 2, 3 and 4. But when actual fluids possessing some viscosity flow through passages, the velocity next to a bounding wall is generally accepted as being zero, taking on larger values away from the wall following a parabolic relationship with distance from the wall. Hence the initial rate of growth of the obstructing film at the cone tip must be zero irrespective of the mean velocity of the oil.

1c. Waiving the objection of (1b), the rate of growth of the obstructing film at the cone tip will be equal to the "oil velocity" divided by the sine of ½ the conical angle made by the free surface *a-a*. Hence when this angle is small the necessary rate of growth of the film should be obtainable with very low oil velocity. No discussion is given in the reference cited by Mr. Prince as to what determines this angle. In his closing discussion last year, Trans. A.I.E.E. V. 50, p. 529, Mr. Prince, in order to account for the greater interrupting capacity of long arcs in oil blast breakers, suggests that for long arcs the angle is smaller. It would seem equally plausible that for small current arcs this angle should be small. Hence it would seem that for long arcs and small currents in circuits of the same speed, smaller "oil velocities" would be necessary. But this contradicts the conclusions which Mr. Prince draws from his Figs. 2, 3 and 4.

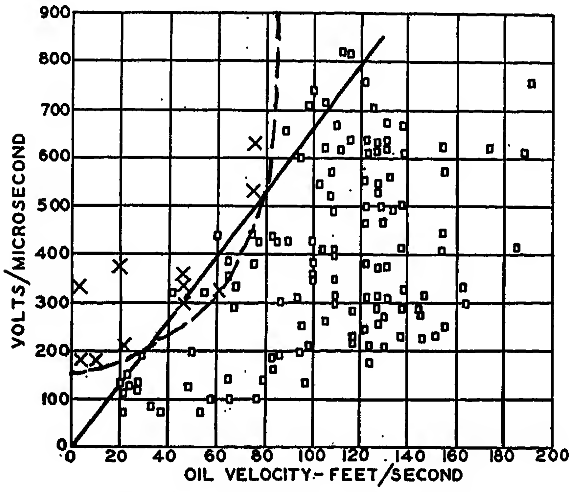

Fig. 4—13,200-Volt Connection

(D. C. Prince, *Elec. Wld.*, February 28, 1931)

1d. No explanation is given why the free surface *a-a* happens to be at just the right place at current zero to start forming immediately the obstructing film. It may be suggested that long before the current zero, the surface *a-a* exists at the proper position with oil rushing up perpendicularly to the surface with the supposed high velocity, but with the oil being decomposed by the arc as fast as it crosses the surfaces. But with oil coming up with a velocity of 100 ft. per sec., and being decomposed, approximately 20,000 liters of gas at atmospheric pressure and temperature would form per second or about 200 liters per half cycle, for a single square inch of surface *a-a*. This is 10 to 100 times as great as the whole volume of gas usually formed in a complete circuit breaker operation. The electrical energy which the arc would need to receive to decompose oil at this rate would be enormous, so that a high arc voltage would be necessary to keep the arc going. Since the high voltage is not available from the circuit, this is another way of saying that the arc will not be able to keep back the advancing oil surfaces, but that it will be squeezed out with development of high voltages. This same argument applies against the oil having a large perpendicular velocity to any surface abutting on the arc and being kept from closing in on the arc by the decomposition of the oil. If the surfaces are kept from closing in by the gas pressure at the arc, then of course, they cannot have the high velocity which Mr. Prince states is necessary. Hence, if surfaces do exist, closing in on the arc with high velocity, there is no reason why their closing in and final cutting off of the arc should be synchronous with a normal current zero.

1e. In his paper of last year, Trans. A.I.E.E. V. 50, p. 508, Mr. Prince says of the oil adjacent to the arc, it "exists alongside it without mixing" and thus suggests that the velocity is tangential to the surface abutting the arc. But such a tangential velocity cannot contribute to the growth of an obstructing film and therefore there should be no relation between such a velocity and the interrupting capacity, in contradiction to the conclusions which Mr. Prince draws from his Figs. 2, 3 and 4.

2. We come now to the data shown in his Figs. 2, 3 and 4, which Mr. Prince regards as the most convincing proofs of his ideas. From these curves Mr. Prince deduces that arc extinction depends upon the relation between the circuit recovery voltage rate and oil velocity alone. Since Mr. Prince gives no account here of the experiments from which these data were taken, it is necessary to consult the reference No. 2 cited by him.

2a. In (1a) and (1b) I have pointed out that the calculated velocity used by Mr. Prince in these curves corresponds to no real velocity in the oil.

2b. In (1c) I have pointed out that according to Mr. Prince himself, for a given "oil velocity" the rate of formation of obstructing film should be greater for long arcs and by a similar argument, for small currents, and therefore is not a function of the oil velocity alone. There is no unique relationship between the rate of growth of an oil barrier and the oil velocity.

2c. The rates of voltage rise in the various circuits are given as calculated from high frequency measurements, but no examples of these calculations are given, so that they may be critically examined.

2d. The rate of voltage rise just after current zero in one and the same circuit will vary widely, depending on the point of the voltage wave at which the circuit was closed. No account seems to have been taken of this factor.

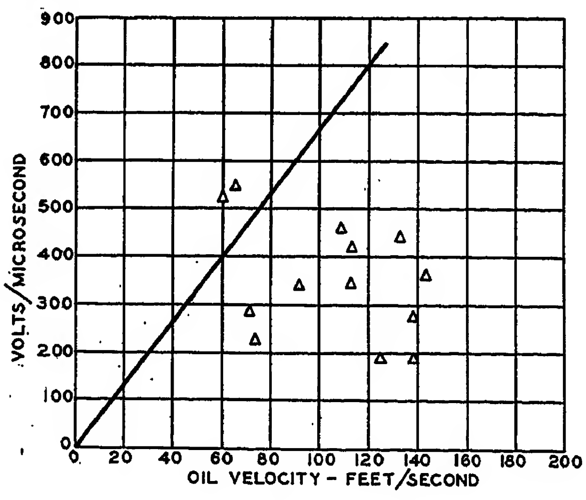

Fig. 5—6,600-Volt Connection

(D. C. Prince, *Elec. Wld.*, February 28, 1931)

2e. For those points marked as failures, was the arc extinguished at a later zero? If so, were those arc extinctions marked as successful in Figs. 2, 3 and 4? If not, why not?

3. Examining the data of Fig. 10 of the reference cited by Mr. Prince, covering supposedly the same tests as Figs. 2, 3 and 4 of this paper, the contention that the condition for interruption is independent of the voltage of the circuit tested is not supported. This may be seen by separating the data for the 13,200-volt, 6,600-volt and 3,800-volt connections as I have done in my

Figs. 4, 5 and 6 of this discussion. In these figures the straight line of "55 kv. per 1/10 inch" has been drawn in.

3a. In my Fig. 4, a curved line would fit the data better than the straight one shown, but there is not a sufficiently dense region of complete failures to draw any curve with any confidence.

3b. From my Fig. 5, no limiting curve can be drawn whatsoever. The data therefore give no information whatsoever as to whether the oil velocity required for a given circuit speed is the same for 6,600 volts as at 13,200 volts. Why are not data given for oil velocities less than 60 ft. per sec., and so little data for circuit speeds of more than 450 volts per microsecond since the curves of Fig. 9, of the cited reference, show that such speeds were readily obtainable?

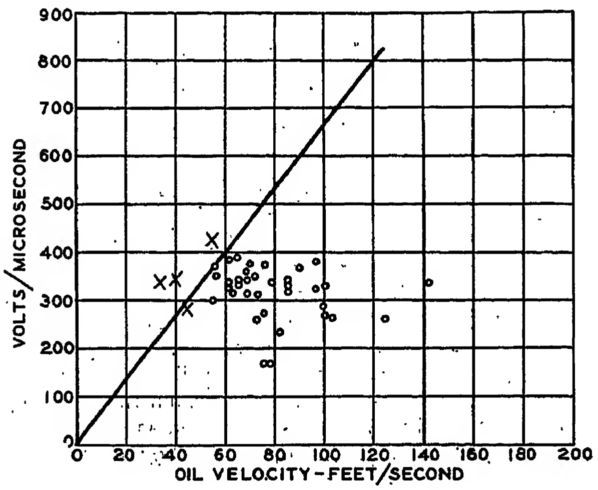

Fig. 6—3,800-Volt Connection

(D. C. Prince, *Elec. Wld.*, February 28, 1931)

3c. From my Fig. 6, we can at most conclude that the limiting curve has one point in common with the "55 kv. per 1/10 inch" line, and even this conclusion seems hardly justifiable with the small amount of data shown. Again, why are not data for higher circuit speeds than 425 volts per microsecond given, since, according to Fig. 9 of the cited reference, such speeds were readily obtainable.

3d. In the reference cited by Mr. Prince, it is stated some 400 tests were made. Fig. 10 in the cited reference shows only 186 points. In the present paper it states that all the tests made are plotted in Fig. 2, but this figure shows only 121 points.

3e. Contradictions exist between points marked as successful and failures in Figs. 10 and 11, of the cited reference and Fig. 2 of this paper. In whatever way these contradictions are straightened out the statements of (3a), (3b) and (3c) do not seem to be affected.

3f. Fig. 3 of the paper shows data at circuit voltages not mentioned in the paper in the cited reference.

3g. In Fig. 3 the points of the 12,000-volt test do not show lack of correlation. The points of the 10,000-volt test do not show lack of correlation. The points of the 6,600-volt test show as good correlation as the points of Fig. 2. The points of the 3,800-volt test are not shown in Fig. 3. When plotted they show perfect correlation.

3h. The points of Fig. 4 of Mr. Prince's paper determine a curve as well (or as poorly) as the points of Fig. 2.

4. At the bottom of page 168, referring to Fig. 5, it is stated that in the plain explosion chamber the arc is uniformly extinguished at the throat. This is glaringly contradicted by Fig. 9 of the paper by Spurck and Strang, Trans. A.I.E.E., V. 50, p. 519.

5. At the top of page 169, Fig. 6 and text, it is stated that tests with multiple throat explosion chamber support the oil blast theory of operation. Data are not given which will permit critical examination of this conclusion.

6. Again, on page 169, tests in a narrow slot are said to support the oil blast theory, but data are not given which will permit critical examination of this conclusion.

7. From the bubble size in Fig. 9, it should be possible to compute the velocity of the oil flowing out of the chamber. It would be interesting to know this figure.

8. On the top of page 170, what is meant by "the arc is clearly subjected to violent washing action"? Is it possible that this is another way of saying that there is a "turbulent inmixing of freshly generated gas".

J. J. Torok and A. M. Opsahl: Mr. Browne's treatment of the expulsion fuse is very interesting and certainly bears out the theory of the turbulent gases. Some time ago in developing the deion flashover protectors we conducted a large number of experiments on extinguishing arcs in fiber tubes. The early experiments on this device were reported in a paper *Experimental Lightning Protector for Insulators*, presented at the Winter Convention 1931. It occurred to us that since gas blast within the tube was caused by the decomposition of the fiber, that the wasting away of the fiber could materially be checked or reduced if the fiber could be impregnated with some substance that would volatilize at a lower value than the fiber. At the same time we were also concerned

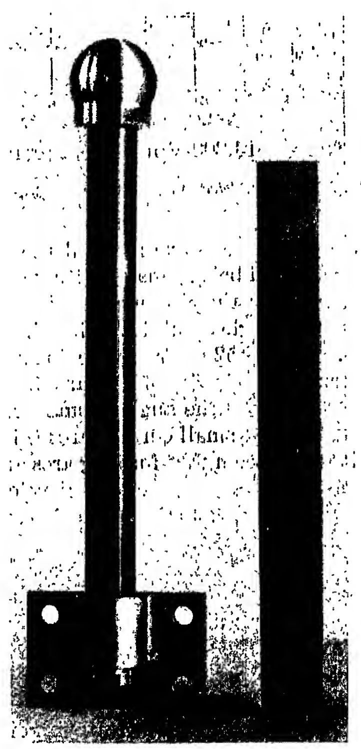

Fig. 7

with another theory which was based upon the condensation of moisture within the chamber. This condensation of moisture formed droplets within the tube and thus materially increased the surface on which ions could be collected.

In some of these tests we wetted the inner wall of the fiber tube with water prior to each test. The results were somewhat startling. We found that the wasting away of the fiber was reduced to about one sixth of its former value. The voltage which could be interrupted on succeeding shots was raised appreciably.

The general conclusions of these tests were that the moisture content of the side walls of the fiber tubes materially improved the operating characteristics of the fiber tube. Thus from the electrical interrupting standpoint it is not harmful for the fiber

tube to be left open to the atmosphere especially where moisture might be collected.

In applying this to service conditions it is not desirable to have a stream of water flowing through the bore of the tube during a rainstorm so that it is essential to either close the upper end or properly shield it. The methods of so doing are illustrated in Figs. 7 and 8. In Fig. 9 the top is vented in such a manner that rain cannot go in directly and the gases will be directed so that they will not come in contact with live parts and thus cause secondary flashover. In Fig. 7 the top is completely closed leaving only the bottom open.

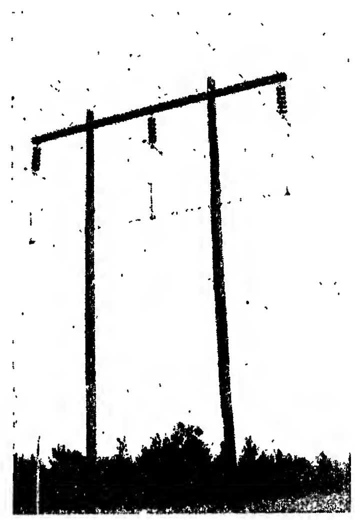

FIG. 8—TYPICAL WESTINGHOUSE EXPULSION ARRESTER

Installation, Camden-Magnolia Line

Of about 1,000 such units put in the field during 1931, the operations that have been reported were successful. Further years of service will yield information as to the relative severity of the duty on the tubes in the field and in the laboratory.

W. A. Hillebrand: The curves presented by Mr. Browne confirm earlier experience with the Poulsen radio arc transmitter, which consists of a d-c. arc, generally between carbon and copper electrodes, in an atmosphere of hydrogen, with a magnetic blowout. But for the accidental application by Valdemar Poulsen about 1905 of an atmosphere of hydrogen to the singing arc, the transmitter that bears his name might not have been developed.

The magnetic blow-out functions as a switch to interrupt the arc at radio frequency. Since 1920 there has been in operation an arc transmitter of this type that, hour after hour, regularly interrupts a thousand kilowatts of energy at the arc terminals. This, it should be noted, is a quantity quite different from the rated interrupting capacity of a circuit breaker. The rate of current interruption varies from 10,000 to 20,000 times per second. Unfortunately for the practical application of this device to circuit breaker work, a magnetic field of the requisite intensity requires a magnet frame weighing in the order of 50 tons.

Reference has been made to the fact that hydrogen is a principal constituent of the gases liberated when an arc takes place under oil. In the Poulsen transmitter the hydrogen atmosphere was often produced by the decomposition of a liquid hydrocarbon allowed to fall drop by drop upon the arc flame.

Mr. Browne states that the difference between the curves of Fig. 6 for oxygen and nitrogen cannot be explained by any difference between their molecular weights. I would like to offer as a possible contributing cause the fact that free electrons can exist in an atmosphere of nitrogen but not in an atmosphere of oxygen.

D. C. Prince: Dr. Slepian and Mr. T. E. Browne, Jr. have contributed most of the discussion relative to theory. Mr. Browne is interested in the relative merits of oil-blast and gas-blast whereas Dr. Slepian bases his discussion on the relative accuracy of a deionization theory as compared with the oil-blast theory. In gas circuit interrupting devices such as Mr. Browne has used, the active agent should be a gas blast of sufficient velocity to displace the arc products by an insulating medium, in his case cool un-ionized gas. In an oil circuit breaker advantage is taken of the fact that oil dielectric strength is of the order of ten times that of gas.

Dr. Slepian has quoted correctly the phrase, "whisking arc products away," but then attacked "whisking away arcs." There is no difference of opinion on the undesirability of trying to break a heavy current arc when by waiting less than one hundredth of a second, it can be broken at a current zero.

On account of the volume of matter represented by the "supporting data" requested by Dr. Slepian, its publication is out of the question. In writing our paper pertinent factors have been taken into consideration in making calculations and no data have been withheld which if presented would support a different conclusion (omitted points were mostly surplus successful operations in the region of greatest density of points). Curves plotted have represented the best available engineering judgment.

When a steel structure is to be designed, an engineer calculates all stresses and multiplies by a factor of safety which may be two, five or more. He then selects a structural section for which tests give a sufficient elastic limit or ultimate strength. Engineering

FIG. 9

judgment may vary the factor of safety but quantitative figures for the stress to be encountered and the physical properties of the steel must be available. The same thing is true of the design and application of oil circuit breakers. Wide changes in duty, as shown by such tests as those at Philo, are not measured in kva. but in recovery rate. The oil-blast theory takes these new factors quantitatively into account. Measurements can be made and calculations based upon them. Factors of safety may be selected as engineering judgment dictates. The theory may ultimately be shown to be in error just as Newton's gravitational theory has been found to be in error, but it will have served its purpose.

High-Voltage Bridge for Measurements of Cables with Grounded Sheaths

BY C. L. DAWES*
Member, A.I.E.E.

and

A. F. DANIEL†
Non-member

Synopsis.—This paper describes a bridge that is adapted to making dielectric measurements of cables whose sheaths are in electrical contact with the ground. A balance to adjust the bridge to the system losses to ground is first made with the test cable disconnected; the bridge is then balanced with the test cable connected. The cable properties such as power loss, power factor and capacitance are then determined directly from this bridge balance. Certain precautions, however, are necessary such as the method of substituting the test cable in circuit and the elimination of the ground currents which may come from the low-voltage system.

INTRODUCTION

PRECISION bridge methods are now available for the dielectric properties of cables when the current through the dielectric can be conducted directly from the sheath to the measuring apparatus. These methods however cannot as a rule be applied to cables whose sheaths are in electrical contact with the ground. There is one method‡ in which a bridge measurement of all the system losses is first made with the test cable disconnected; a second bridge measurement is then made with the test cable in circuit. The difference in the power measurements gives presumably the power loss in the cable dielectric. This method does not give directly the electrical properties of the cable (power, power factor, capacitance). Also, unless special precautions are taken, the connecting of the cable to the system may cause a change in the ground currents other than that of the cable under test. The authors have developed a bridge method which measures directly and with a high degree of precision the values of the electrical properties of the test cable.

GROUNDED-BRIDGE METHOD

A simplified diagram of the method is shown in Fig. 1. The cable to be tested is shown as C_5. The transformer case is shown as being insulated from ground. This is not necessary, but is preferable in that all loss currents from windings to case return immediately to the high-voltage winding thus reducing the loss currents through the ground which must be compensated by the bridge. C_2 is a high-voltage condenser having a capacitance of a few hundred micro-microfarads. At any particular voltage setting, its capacitance and losses should remain substantially constant during the time required for making a measurement. In our measurements we used a 10-ft. length of high-voltage cable having a capacitance of the order of 800 $\mu\mu f$. It is desirable that this capacitance should be of such magnitude that its charging current is at least somewhat larger than the stray charging and loss currents from the system to ground. M is a mutual inductance; R_1 and R_2 are ordinary variable resistance decades. C_1 is a fixed standard air condenser such as is used with the usual high-voltage bridge. C_2, M and R_2 constitute branch A of the bridge; C_1 and R_1 constitute branch B of the bridge. L is a calibrated variometer (self-inductance) and R_5 is a variable resistance decade. L and R_5 are connected in series between the cable sheath (ground) and the low-voltage end of the high-side winding of the transformer. C_5, L and R_5 constitute branch C of the bridge.

One terminal of the secondary of M is grounded at b and the detector D is connected between the ground and point a at the junction of R_1 and C_1. The detector D is a tuned magnetic-vane galvanometer and has already been described.[1]

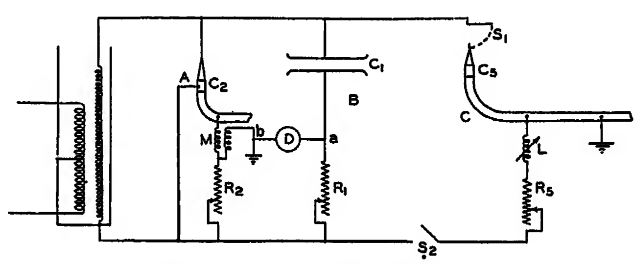

FIG. 1—SIMPLIFIED DIAGRAM OF GROUNDED BRIDGE

Switches S_1 and S_2 are in the high- and low-voltage wires which connect the cable to be measured to the bridge terminals. In making the measurements switches S_1 and S_2 are first opened. This isolates the cable from the rest of the system except through the ground connection and gives a bridge, the two branches of which are A and B. This bridge is of the same type that has been in use in our laboratories for some time[1] past except that the secondary of the mutual inductance M and the detector D are now grounded at b. The bridge is then balanced by varying M and R_1. All the loss currents of the system to ground must flow to point b and return to the transformer through the secondary of the mutual inductance M. Hence this balance does not depend on the dielectric characteristics of C_2 alone

*Assoc. Prof. of Elec. Engg., Harvard University.

†Research Associate in Elec. Engg., Harvard University.

‡This method is in use at the Commonwealth Edison Company for measuring the characteristics of experimental 1,000-ft. lengths of 76-kv. (to ground) cables under life test.

Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 25-29, 1932.

1. For references see Bibliography.

but rather on the characteristics of C_2 in combination with all stray capacitances and leakances to ground. Moreover, since current flows in the secondary of M, its reading cannot be used for computing the power factor of C_2 or C_2 in conjunction with the system impedance to ground.

After this balance has been made, switches S_1 and S_2 are closed, thus connecting the cable C_5 between the high-voltage side of the bridge and ground and also the variable self-inductance L and resistance R_5 in series, between ground and the low-voltage end of the transformer winding. Were S_1 alone closed, all the cable current must flow from the cable sheath to ground and leave the ground at b to return to the transformer winding through the secondary of the mutual inductance M. In so doing this current must disturb the bridge balance already obtained. If the system losses to ground have not been changed by the closing of switch S_1, the original bridge balance can only be restored when *none* of the current through C_5 returns to the transformer through M. Obviously this condition is realized only when *all* the current through C_5 flows through L and R_5. By closing switch S_2 and making proper adjustment of L and R_5, this condition may be realized and is indicated by the detector D again reading zero. The bridge formed by branches B and C will be recognized as the Wien modification of the Maxwell Bridge.[4]

The operation of the bridge may also be regarded from the point of view that since point a has already been brought to ground potential when the detector again reads zero, no difference of potential exists between the ground connection at b and the cable sheath of C_5; hence no current flows between these two points, and the current in L and R_5 must be the same as that in the cable.

Under the foregoing conditions of balance, the current in L and R_5 is the same as that in C_5 and

$$\frac{C_5}{C_1} = \frac{R_1}{R_5} \text{ (very nearly)} \tag{1}$$

The power factor

$$\text{Power factor} = \frac{L\,\omega}{R_5} \tag{2}$$

R_5 includes the resistance of the variometer L. A self-inductance may be substituted for M and the ground made at the low-voltage plate of C_2. However, a mutual inductance is particularly well adapted to this ground connection since the stray impedances to ground may require either a positive or a negative phase displacement for balance, and with mutual inductance, both are obtained equally well. It will be noted that arm A of this bridge acts almost in the same manner as the well-known Wagner ground.[2]

Limitation of Bridge Types

The types of bridge which may be used for this method of cable measurement are limited since for each measurement the branch B of the bridge must remain invariable and the cable sheath of C_5 must be connected directly to the detector. The first limitation precludes the use of the Schering Bridge[3,4] in which the balance is effected by varying R_1 and a condenser shunted about R_1. The second limitation makes it undesirable to use the Heaviside Bridge of the mutual inductance type[1] since in the simplest form of this bridge the primary of the mutual inductance is in series with the cable sheath of C_5.

Guarding and Shielding

The usual guarding and shielding which are necessary in high-voltage, low power-factor measurements must be used with this bridge. Also, further precautions are necessary to prevent change of system losses to ground when the cable C_5 is switched in circuit.

Although no measurement of cable C_2 is made, guard rings at its ends are desirable to prevent end discharges disturbing the galvanometer balance. These guard rings need not be balanced to sheath potential but may be connected directly to the low-voltage end of the transformer winding as shown in Fig. 2, which gives the

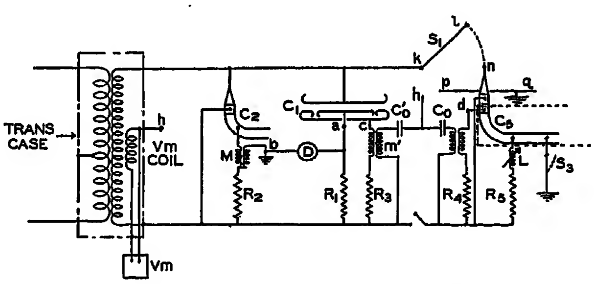

Fig. 2—Detailed Diagram of Grounded Bridge

complete diagram of connections. As is customary in conventional bridge methods the low-voltage plate of the air condenser C_1 and the leads connecting thereto must be shielded and the shielding brought to the potential of the low-voltage plate. This is done by means of the resistance R_3 and the mutual inductance m' whose primary is connected across the voltmeter coil in series with C_0'. During *this* balance the detector is connected between points a and c.

In a like manner the guards and shielding of the test cable C_5 are brought to the potential of the active sheath by means of R_4 and the mutual inductance m. It is to be noted that with the exception of the guards of C_2 all shielding is at ground potential although not actually grounded. To prevent end discharges entering the guard circuit, and disturbing the galvanometer deflections, double guarding may be used with cable C_5[1].

Some care must be taken in the manner in which switch S_1 is closed. The accuracy of the method depends on the losses to ground of the system remaining unchanged when C_5 is switched in circuit. If the live parts, kl of switch S_1 (see Fig. 2) are too near the cable,

the system will pick up charge as may be proved by opening S_3 and closing S_2. Hence, in our experiments kl was a long lead of No. 1, bare solid wire about 20 ft. (6 m.) long, connected permanently to the high-voltage source at k. Connection to C_5 was made by *swinging* this lead parallel to the ground until it came in contact with the cable copper at n. In both the open and the closed positions care was taken that kl had the same relative position to ground so that its loss to ground did

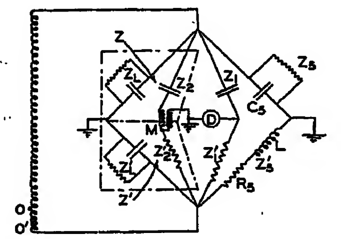

FIG. 3—CONVENTIONAL DIAGRAM OF GROUNDED BRIDGE

not change. Furthermore when point l is connected to point n some of the loss from kl would normally be transferred from ground to the cable shielding, thus causing a variation in ground loss and causing error. To eliminate this source of error a grounded shield pq was interposed between the cable shielding and kl to intercept this loss current from kl and divert it to ground. With a long length of test cable almost entirely buried in the ground, percentage errors from this source naturally would not be large.

EQUIVALENT BRIDGE CIRCUITS

The connections of this bridge in the usual conventional form are shown in Fig. 3. The high-voltage bushing of the transformer and the high-voltage system have an equivalent capacitance and leakance to ground which may be denoted by Z_L. Some intermediate point in the transformer winding such as o must be at ground potential. If the case is non-grounded as shown in Figs. 1 and 2, it and the portion of the winding oo' form an equivalent capacitance and leakance to ground which may be represented by Z_L'. If the case is grounded Z_L' represents the impedance to case of the portion oo' of the winding. Z_2 and Z_2' constitute the arm A of the bridge, Fig. 1; Z_1 and Z_1' constitute the arm B, consisting of the standard air condenser and R_1, Fig. 1; Z_5 and Z_5' constitute the arm C, Fig. 1, consisting of the test cable C_5, the self-inductance L and the resistance R_5.

In the bridge itself Z_L and Z_2 combine to form an equivalent impedance to ground Z; likewise Z_L' and Z_2' combine to form an equivalent impedance to ground Z'. The first balance (with switches S_1 and S_2, Figs. 1 and 2 open) causes adjustments among Z_2, Z_2', and Z_1' such that

$$\frac{Z}{Z'} = \frac{Z_1}{Z_1'} \tag{3}$$

In the second balance, with switches S_1 and S_2 closed, Z_5' is adjusted until

$$\frac{Z_5}{Z_5'} = \frac{Z_1}{Z_1'} \tag{4}$$

The mathematical proofs of (3) and (4) for bridges in general may be found in text books[2,4] and are well known. For simplicity, the guard circuits are omitted in Fig. 3. They would merely constitute two more bridge circuits similar to those shown and having their respective arms in the proportions given in (3) and (4).

LOW-VOLTAGE SYSTEM DISTURBANCES

In our laboratory measurements we were able to verify the accuracy of the method by interposing a switch S_3, Fig. 2, in the ground connection. When S_3 is opened, the branches B and C constitute a simple Wien-Maxwell bridge[4] with the branch A now constituting a true Wagner ground. If the method is correct, little or no change in the balance should occur whether S_3 is closed or opened, provided the bridge system is already in proper balance. Errors in the high-voltage system due to inadequate shielding, and the change in ground loss brought about by the movement of the lead kl, were soon appreciated and eliminated in the manner already described.

Another source of error was found to be due to the changes in the ground relations of the low-voltage system caused by the increased capacitive load occurring when C_5 is connected to the transformer secondary. When switch S_1 is closed the secondary voltage of the transformer rises due to the increased capacitive load. The high-side voltage is restored to its original value by reducing the voltage of the low-voltage side, including that of the line running from the transformer primary back to the alternator. This causes variations in the

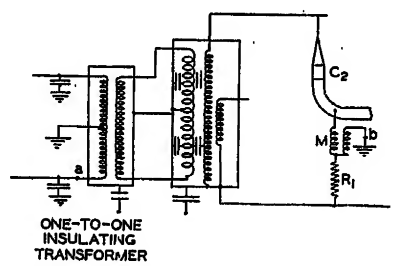

FIG. 4—STRAY CAPACITANCE IN GROUNDED BRIDGE

capacitive and leakage currents to ground from this entire system. If by chance any of this current enters the low-voltage system at b and through the secondary of M, Figs. 1 and 2, any change of voltage in the low-voltage system changes this current. This effect may cause large errors. Also to this effect must be added the effect of capacitance and leakance between the high-voltage and the low-voltage winding of the transformer, as is indicated in Fig. 4. Apparently, there is no single connection which will make all such errors zero, particularly if the capacitances are unsymmetrical, but

they can be made very small. It was found that the most accurate results were obtained when the connections shown in Fig. 4 were used. The losses in the low-voltage system back to the generator were eliminated by using a one-to-one insulating transformer and grounding the system back to the alternator at one point. All ground loss currents could thus return to this system through this connection.

The case of this one-to-one transformer was connected to the case of the test transformer and to the middle point of the low-voltage winding of the test transformer. A study of Fig. 4 shows that any change in capacitive and leakage currents of this system do not flow through the ground connection at b except the capacitive currents between primary and secondary of the insulating transformer. Since these windings are at low voltage, changes in their capacitive currents are small. If the low-voltage system is grounded at its neutral point a condition of symmetry is produced which again minimizes changes in ground currents caused by change of voltage. When one side of the low-voltage system was grounded at a, Fig. 4, rather than at the neutral point little error was found to result. With long lengths of cable such as would ordinarily be measured by this method, the foregoing errors, whose magnitudes are determined almost entirely by the voltage and not by the losses in the test cable, will all be small, proportionately.

Experimental Tests

In the laboratory the cable was not actually installed in the ground, which made it possible to interpose a switch S_3, Fig. 2, in the lead connecting the sheath to ground. By opening S_3 and switching the detector between point a and the sheath C_5 a true Wien-Maxwell impedance bridge is formed, so that it becomes possible to check the accuracy of the measurements which are made when the sheath is grounded. Such check measurements were made on a 31.5 ft. (8.8 m.) length of 00, 9/32 in. (0.715 cm.), wall, impregnated-paper insulated cable. The results of these tests are given in Table I.

TABLE I
Frequency = 60 cycles. C_1 = 120 $\mu\mu f$.

S_3	E (kv.)	R_1	R_2	R_6	L (Mh.)	Power factor	C ($\mu\mu f$. per ft.)	Watts per ft.
Closed	11.42	5780	200	346.5	5.5	0.598	63.5	0.0187
Open	11.42	5780	200	347.8	5.4	0.584	63.3	0.0182
Closed	16.8	5812	200	347.9	5.60	0.606	63.7	0.0411
Open	16.8	5812	200	348.9	5.45	0.588	63.5	0.0497
Closed	22.4	5855	200	348.1	8.75	0.948	64.0	0.0115
Open	22.4	5855	200	349.3	8.60	0.927	63.8	0.0112
Closed	28.0	7213	200	427.7	13.25	1.17	64.2	0.213
Open	28.0	7213	200	428.7	12.80	1.13	64.1	0.222
Closed	28.0	5676	200	334.7	8.4	0.946	64.5	0.180
Open	28.0	5676	200	336.1	8.75	0.984	64.4	0.187
Closed	33.6	5723	200	339.6	14.5	1.49	64.2	0.408
Open	33.6	5723	200	340.7	15.0	1.44	64.0	0.393

The last two sets of measurements were taken three days later than the preceding ones. During this period the cable underwent slight change so that these last data are not continuous with those which precede it. It is to be noted that the maximum difference between corresponding measurements is of the order of 4 per cent which is not large when the character of the measurement is considered.

It may be objected that this method involves too many bridge balances. With the conventional bridge having proper shielding at least three balances should be made. Also when balances for one voltage have been made, subsequent balances are usually made quite readily.

The authors wish to express their appreciation to Dean H. E. Clifford of the Harvard Engineering School for his helpful suggestions in the preparation of this paper.

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A High Sensitivity Power Factor Bridge

BY W. B. KOUWENHOVEN* and ALFREDO BAÑOS, JR.†
Member, A.I.E.E. Associate, A.I.E.E.

Synopsis.—This paper describes an a-c. bridge of high precision, used for power factor measurements in one of the dielectric investigations being carried on at the Johns Hopkins University. The bridge, a modified form of the Schering bridge, possesses several novel features and advantages. The detecting instrument is a moving coil a-c. galvanometer; its field excitation is supplied from a phase shifting transformer, which permits obtaining independent ratio and phase angle balances. A shielded transformer electrostatically isolates the galvanometer from the bridge circuits.

This bridge is completely shielded and guarded and the analytical theory of the resulting mesh connection is given in the paper. The mathematical treatment is general and may be applied to any similar network. A full discussion is given of the effects upon the balance relation of various sources of error, for example, as failure to balance guard circuits properly and the presence of leakage resistance between measuring and guard circuits. Experimental verification of the equations is presented.

Power factors of specimens of cable material have been measured ranging from 0.00007 to 0.16 with a maximum variation of ± 0.000005.

THE Schering bridge is probably the most widely used a-c. bridge for the measurement of the capacitances and phase defect angles of dielectrics under high-voltage gradients. In a study of the properties of high-voltage cables carried on in the Electrical Laboratories of the School of Engineering of The Johns Hopkins University we have used a completely shielded and guarded Schering bridge[1] for a number of years.

About two years ago, under the auspices of the Utilities Research Commission, an investigation was begun of the properties of cable compounds and papers and of the characteristics that occur after impregnation. In this work it became necessary to modify the Schering bridge in order to obtain the desired range and sensitivity. The bridge that finally resulted is completely shielded and guarded and possesses several novel features.

A bridge has been developed in which it is possible to balance the guard circuits without the use of a second galvanometer or disturbing in any way the main galvanometer connections. It is shown that in this bridge it is not necessary to balance the guard circuits for phase but only for magnitude.

The Bridge

A diagram of the bridge connections is given in Fig. 1, where C_1 is the specimen and C_2 the air capacitor. The latter is adjustable and its high-tension plate is so mounted that any leakage currents from it flow directly to ground and not into its guard circuit.[2] Both the specimen and the air capacitor are provided with guard ring electrodes. The leads from their main or measuring electrodes to the points A and B of the bridge are one-eighth inch (3. mm.) brass rods shielded by one inch (2.54 cm.) diameter tubes. The central conductors are supported at approximately three-foot (1 meter) intervals by small hard rubber washers. Each shielding tube is connected to its proper guard ring as may be seen from the figure.

*Professor of Electrical Engineering, Johns Hopkins University.

†Research Assistant, Johns Hopkins University.

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The capacitance between the main electrode with its lead and the guard ring with its shield is 470 $\mu\mu f$ for the specimen and 490 $\mu\mu f$ for the air capacitor. It is essential for accurate measurement that the insulation resistance of these two capacitances be maintained *equal to infinity*, as measured with the Megger.

The physical arrangement of the apparatus is such that the specimen and air capacitor may be quickly

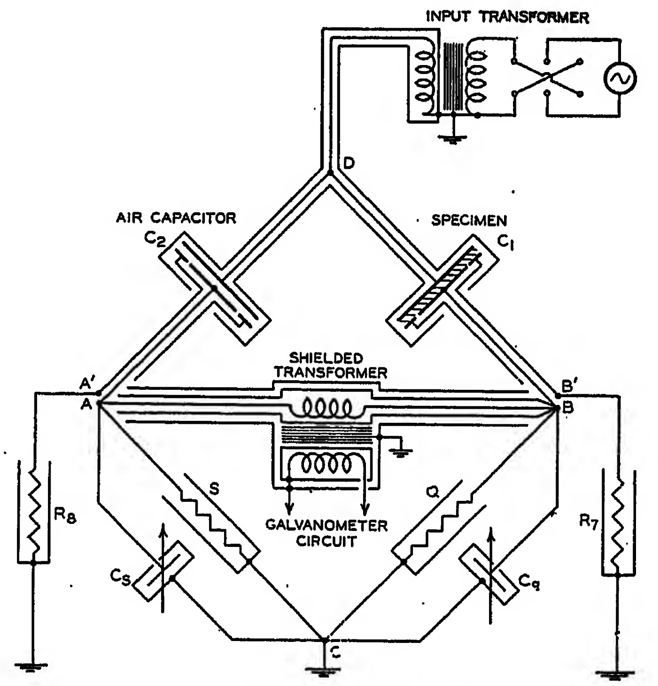

Fig. 1—Bridge Circuit—Diagram of Connections

interchanged. It is also a simple matter to disconnect the specimen and substitute an air capacitor in its place for making check measurements.

One feature of this bridge, originally used by Hartshorn[3] in low-voltage work, is the use of two variable air capacitors Cs and Cq in parallel with the S and Q arms respectively. The capacitance Cq consists of the variable capacitor shown in the figure plus the capacitance to ground of the detector arm shield, which is connected to the point B of the bridge. In normal operation Cq is kept at a fixed value and balance is obtained

by varying Cs, a variable calibrated air capacitor. The use of the capacitor Cq permits the neutralization of the fixed capacitance of the bridge and the measurement of very small values of power factor.

As Cq includes certain fixed capacitances it is necessary to determine its value. This is accomplished by substituting an air capacitor for the specimen, and balancing by adjusting Cs, using a 1 to 1 bridge. Then the two high-voltage air capacitors are interchanged and the balance checked. The same value of Cs should hold for both cases to within the sensitivity of the bridge, a phase angle whose cosine is $\pm 5 \times 10^{-6}$. Under these conditions and a ratio of one to one the value of Cq equals that of Cs, the calibrated air capacitor.

The detector is a Leeds and Northrup a-c. moving coil type of galvanometer, which is connected to the bridge through an electrostatically shielded transformer, as shown in Fig. 2. The magnetic field of the galvanometer is excited from the secondary of a phase shifting transformer. The deflection of the galvanometer depends upon the phase relation between its magnetic field and the current in its moving coil. When these

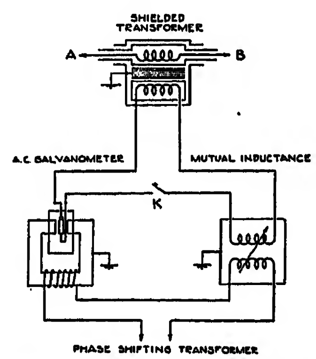

FIG. 2—GALVANOMETER CIRCUIT—DIAGRAM OF CONNECTIONS

two are in phase the deflection is a maximum and when they are in quadrature zero.

In balancing any impedance bridge two conditions must be satisfied, the ratio or magnitude balance and the phase balance. The currents produced by these two factors are in quadrature and it is a simple matter to bring the galvanometer field into phase with either component by adjusting the position of the secondary of the phase shifting transformer. This feature enables the operator not only to balance the bridge for either ratio or phase angle separately and independently, but also to adjust properly the magnitude of the guard resistances, R_7 and R_8, without either disturbing the connections of the main galvanometer or the use of a second detector.

A variable mutual inductance is connected in series with the galvanometer to neutralize the e.m.f. induced in its moving coil by the a-c. field. The value of the mutual inductance is adjusted so as to keep the galvanometer reading on the scale, that is, by making the electrical and mechanical zeros coincide. Balance of the bridge is obtained when there is no change in the galvanometer deflection[4] upon reversal of the input e.m.f.

The simple balance relations of this bridge are: ratio

$$C_1 = C_2 \, S/Q \tag{1}$$

and the phase angle ψ_1, of the specimen

$$\psi_1 = \omega \, Cs \, S - \omega \, Cq \, Q \tag{2}$$

Where ω equals $2\,\pi$ times the frequency.

The power supply for the bridge and the primary of the phase shifting transformer are taken from a three phase "General Electric Company" sine wave generator driven by a motor supplied by the University storage battery. The sensitivity of the bridge is ample and for phase angle corresponds to an angle whose cosine is $5. \times 10^{-6}$. Values of capacitance ranging from 40 $\mu\mu$f to 1,500 $\mu\mu$f and specimen power factors from 0.007 to 16 per cent have been successfully measured. The bridge is usually operated at 60 cycles and 1,500 volts alternating current.

OPERATION OF THE BRIDGE

In the operation of the bridge the first step is the proper adjustment of the phase shifting transformer. This is attained in the following manner:

Using the specimen, C_1, and air capacitor, C_2, in the high-voltage arms, and having set the ratio arms Q and S to 5,000 ohms each, as tentative values, low-voltage is applied to the bridge. Then the operator proceeds to find by trial the phase shifter setting which will give a minimum deflection when the ratio arms are upset by, say, 1,000 ohms in 5,000. This gives the approximate phase shifter setting for the phase angle balance. The phase shifter is then thrown through 90 deg. to the "ratio" setting and the ratio balance roughly determined. The process is then repeated until it is possible to have an unbalance of several thousand ohms in the ratio arms remain undetected when the phase shifter is in the "phase angle" setting. These adjustments give accurately the phase angle and ratio settings of the secondary of the phase shifting transformer.

In balancing the bridge all four low-voltage arms, R_8, S, Q, and R_7, are set at some tentative values. With the phase shifter on the ratio setting and Q at 5,000 ohms, S is adjusted to the nearest ohm. If Q and S differ materially from each other the spacing of the standard air capacitor is varied to bring the bridge closer to a one to one ratio.

Once a satisfactory ratio of Q and S is obtained, the operator proceeds to balance the guard circuit of the specimen. With the phase shifting transformer in the ratio position the operator connects the points $B - B'$ of the bridge by means of a short lead and then adjusts the guard resistance, R_7, until the upset in balance caused by this procedure disappears. With R_7 at its proper value for magnitude balance, the operator removes the short circuit from across $B - B'$, places it on $A - A'$ and proceeds to adjust R_8 in the same manner as R_7. These adjustments of R_7 and R_8 are for magnitude only and not for phase. The magnitude balance

is thus obtained using the main galvanometer as a detector, but without disturbing its connections in any way. The proof of the correctness of this procedure will be discussed later.

After the proper settings of R_7 and R_8 are obtained, the ratio balance is once more checked; usually the balance is not off more than five ohms in 5,000, unless the preliminary settings of R_7 and R_8 were considerably out.

The full test voltage is now applied to the bridge and the operator obtains the final ratio balance, after rechecking the guard resistances for magnitude balance. The phase shifter is then rotated through 90 deg. to the phase angle position and the phase balance obtained by adjusting the variable air capacitor, C_s.

The power factor of the specimen is calculated in accordance with equation (2). It will be shown that this simple relation gives the correct value of the power factor, despite the fact that the guards have been balanced for magnitude only; provided the leakage resistances existing between the guarding systems and their respective measuring circuits are infinity.

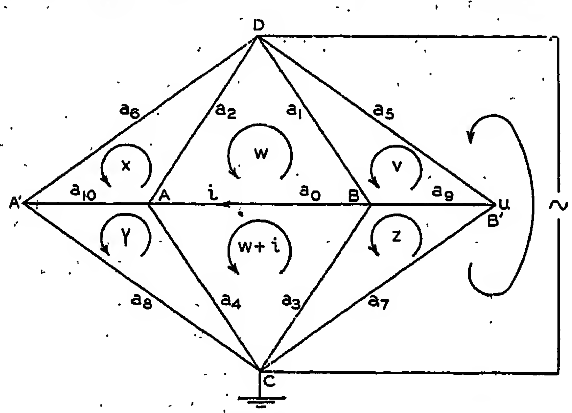

FIG. 3—GENERALIZED MESH DIAGRAM

MESH DESIGN

The mesh diagram of the bridge is given in Fig. 3. This diagram is a general one and may be applied to almost any shielded bridge. The complex impedance operators are represented by $\bar{a}_1$, $\bar{a}_2$, etc. Where $\bar{a}_1$, $\bar{a}_2$, $\bar{a}_3$ and $\bar{a}_4$ represent the measuring circuits of the bridge, and $\bar{a}_5$, $\bar{a}_6$, $\bar{a}_7$, and $\bar{a}_8$ the guard circuits. The operator $\bar{a}_1$ belongs to the measuring circuit of the specimen and $\bar{a}_5$ to its guard. In like manner $\bar{a}_2$ and $\bar{a}_6$ belong to the measuring and guard circuits of the air capacitor, respectively. The operator $\bar{a}_9$ represents the impedance existing between the measuring and guard circuits of the specimen and $\bar{a}_{10}$ performs the same function for the air capacitor circuit. The operator $\bar{a}_0$ expresses the impedance of the galvanometer arm of the bridge.

Using the cyclic currents of Maxwell[5] we obtain a set of six simultaneous equations. Table I below gives the coefficients of the cyclic currents of the generalized mesh.

TABLE I—THE COEFFICIENTS OF THE CYCLIC CURRENTS.

Mesh	i	v	w	x	y	z	u
$A\,A'\,D$	0	0	$-\bar{a}_2$	$(\bar{a}_2 + \bar{a}_6 + \bar{a}_{10})$	$-\bar{a}_{10}$	0	0
$A\,B\,D$	$-\bar{a}_0$	$-\bar{a}_1$	$(\bar{a}_1 + \bar{a}_2)$	$-\bar{a}_2$	0	0	0
$B\,B'\,D$	0	$(\bar{a}_1 + \bar{a}_5 + \bar{a}_9)$	$-\bar{a}_1$	0	0	$-\bar{a}_9$	$\bar{a}_5$
$A\,A'\,C$	$-\bar{a}_4$	0	$-\bar{a}_4$	$-\bar{a}_{10}$	$(\bar{a}_4 + \bar{a}_8 + \bar{a}_{10})$	0	0
$A\,B\,C$	$(\bar{a}_0 + \bar{a}_3 + \bar{a}_4)$	0	$(\bar{a}_3 + \bar{a}_4)$	0	$-\bar{a}_4$	$-\bar{a}_3$	0
$B\,B'\,C$	$-\bar{a}_3$	$-\bar{a}_9$	$-\bar{a}_3$	0	0	$(\bar{a}_3 + \bar{a}_7 + \bar{a}_9)$	$\bar{a}_7$

The current, i, through the galvanometer circuit may be obtained by the solution of the simultaneous equations by means of determinants. For balance the galvanometer current must equal zero and this will only be fulfilled when the determinant for the numerator is zero.

Solving this determinant and equating to zero the complete balance relation is obtained, equation (3), for the generalized network, namely

$$\frac{\bar{a}_1\,\bar{a}_4}{\bar{a}_2\,\bar{a}_3} = \frac{\bar{a}_5\,\bar{a}_9 + \bar{a}_7\,(\bar{a}_1 + \bar{a}_5 + \bar{a}_9)}{\bar{a}_7\,\bar{a}_9 + \bar{a}_5\,(\bar{a}_3 + \bar{a}_7 + \bar{a}_9)} \cdot \frac{\bar{a}_8\,\bar{a}_{10} + \bar{a}_6\,(\bar{a}_4 + \bar{a}_8 + \bar{a}_{10})}{\bar{a}_6\,\bar{a}_{10} + \bar{a}_8\,(\bar{a}_2 + \bar{a}_6 + \bar{a}_{10})} \tag{3}$$

Equation (3) may also be expressed in another form, (4), which is usually more convenient to use.

$$\frac{\bar{a}_1\,\bar{a}_4}{\bar{a}_2\,\bar{a}_3} = \frac{\bar{a}_5 + \bar{a}_7 + \dfrac{\bar{a}_7}{\bar{a}_9}\,(\bar{a}_1 + \bar{a}_5)}{\bar{a}_5 + \bar{a}_7 + \dfrac{\bar{a}_5}{\bar{a}_9}\,(\bar{a}_3 + \bar{a}_7)} \cdot \frac{\bar{a}_6 + \bar{a}_8 + \dfrac{\bar{a}_6}{\bar{a}_{10}}\,(\bar{a}_4 + \bar{a}_8)}{\bar{a}_6 + \bar{a}_8 + \dfrac{\bar{a}_8}{\bar{a}_{10}}\,(\bar{a}_2 + \bar{a}_6)} \tag{4}$$

The terms on the right hand side of equations (3) and (4) are correction terms that express the factors introduced into the simple bridge relation by the presence of the guard circuits. These equations may be expressed in the form of

$$\frac{\bar{a}_1\,\bar{a}_4}{\bar{a}_2\,\bar{a}_3} = \bar{k}_1\,\bar{k}_2 \tag{5}$$

Where
$$\bar{k}_1 = \frac{\bar{a}_5 + \bar{a}_7 + \dfrac{\bar{a}_7}{\bar{a}_9}\,(\bar{a}_1 + \bar{a}_5)}{\bar{a}_5 + \bar{a}_7 + \dfrac{\bar{a}_5}{\bar{a}_9}\,(\bar{a}_3 + \bar{a}_7)}$$

and
$$\bar{k}_2 = \frac{\bar{a}_6 + \bar{a}_8 + \dfrac{\bar{a}_6}{\bar{a}_{10}}\,(\bar{a}_4 + \bar{a}_8)}{\bar{a}_6 + \bar{a}_8 + \dfrac{\bar{a}_8}{\bar{a}_{10}}\,(\bar{a}_2 + \bar{a}_6)}$$

It is interesting to note that if the guard circuits are balanced with respect to their corresponding bridge circuits, *i. e.*,

$$\frac{\bar{a}_1}{\bar{a}_3} = \frac{\bar{a}_5}{\bar{a}_7} \text{ and } \frac{\bar{a}_2}{\bar{a}_4} = \frac{\bar{a}_6}{\bar{a}_8}$$

that the generalized expression reduces to the simple bridge relation given in

$$\frac{\bar{a}_1\,\bar{a}_4}{\bar{a}_2\,\bar{a}_3} = 1 \qquad (6)$$

If no guard circuits are used in the bridge or if the impedances expressed by $\bar{a}_9$ and $\bar{a}_{10}$ are equal to infinity, equation (4) again reduces to (6) the simple balance relation for a wheatstone network.

Equation (6) contains the complex operators of the four arm impedance bridge; each operator having the general form $R \pm jX$. The balance of the bridge requires two adjustments, ratio and phase[6] as stated in the introduction. The ratio and phase balance relations, readily deduced from equation (6), are given (7) below:

$$\left.\begin{aligned} \frac{Z_1\,Z_4}{Z_2\,Z_3} &= 1 \\ (\phi_1 + \phi_4) - (\phi_2 + \phi_3) &= 0 \end{aligned}\right\} \qquad (7)$$

Where Z_1, Z_2, etc., are absolute values and ϕ_1, ϕ_2, etc., are the corresponding phase angles of their respective complex impedance operators.

In like manner the correction terms $\bar{k}_1$ and $\bar{k}_2$ of equation (5) are complex quantities for which K_1 and K_2 are their respective absolute values and ϕ_{K1} and ϕ_{K2} their phase angles. For the guarded and shielded bridge the general balance relations are (8)

$$\left.\begin{aligned} \frac{Z_1\,Z_4}{Z_2\,Z_3} &= K_1\,K_2 \\ (\phi_1 + \phi_4) - (\phi_2 + \phi_3) &= \phi_{K1} + \phi_{K2} \end{aligned}\right\} \qquad (8)$$

Correction Terms

It is evident from equation (8) that the simple ratio and phase angle balance relations mentioned under the description of the bridge must be modified to take care of the correction terms, $\bar{k}_1$ and $\bar{k}_2$ introduced by the presence of the guarding and shielding circuits and that these terms must be evaluated.

It is well to point out here that these correction terms are actually present in every four arm impedance bridge. In unshielded bridges their evaluation is impossible. The use of guards and shields serves to give definite values to these terms and to make their accurate determination feasible.

In order to evaluate the correction terms we must substitute the values of the general operators given below into equation (5)

$$\left.\begin{aligned}
\bar{a}_1 &= \rho_1 - \frac{j}{\omega\,C_1} = \frac{1}{\omega\,C_1}(\psi_1 - j) \\
\bar{a}_2 &= \frac{-j}{\omega\,C_2} \\
\bar{a}_3 &= \frac{1}{1/Q + j\,\omega\,C_q} = Q\,(1 - j\,\phi_q) \\
\bar{a}_4 &= \frac{1}{1/S + j\,\omega\,C_s} = S\,(1 - j\,\phi_s) \\
\bar{a}_5 &= \frac{1}{\omega\,C_5}(\psi_5 - j) = \frac{m_1}{\omega\,C_1}(\psi_1 - j) \\
\bar{a}_6 &= -\frac{j}{\omega\,C_6} = -\frac{j\,m_2}{\omega\,C_6} \\
\bar{a}_7 &= R_7\,(1 - j\,\phi_7) = m_1\,Q\,(1 - j\,\phi_7) \\
\bar{a}_8 &= R_8\,(1 - j\,\phi_8) = m_2\,S\,(1 - j\,\phi_8) \\
\bar{a}_9 &= \frac{1}{1/W_9 + j\,\omega\,C_9} \\
\bar{a}_{10} &= \frac{1}{1/W_{10} + j\,\omega\,C_{10}} \\
m_1 &= \frac{C_1}{C_5} \\
m_2 &= \frac{C_2}{C_6}
\end{aligned}\right\} \qquad (9)$$

Where ρ_1 is the equivalent series resistance to account for the loss in the specimen capacitor C_1; ψ_1 equals $\omega C_1 \rho_1$, the phase defect angle of the specimen; the angle ϕ_q equals $\omega C_q Q$, the phase angle of the a_3 arm, and ϕ_s equals $\omega C_s S$, the phase angle of the a_4 arm. The angles ϕ_7 and ϕ_8 express the respective phase angles of the R_7 and R_8 arms and are mainly due to capacitance to earth of the shielding. The capacitance of the high-tension electrode of the specimen to its guard is C_5 and ψ_5 its phase defect angle, and the capacitance of the high side of the air capacitor to its guard is C_6. In the operators we have assumed that the phase defect angles of the specimen and its guard are the same, namely that ψ_1 equals ψ_5, and also that both the air capacitor C_2 and its guard C_6 have zero phase defect angles.[2] The capacitance existing between the measuring circuit and the shielding circuit of the specimen is C_9 and the corresponding capacitance for the air capacitor is C_{10}. Both of these capacitances, C_9 and C_{10} have leakage resistances, W_9 and W_{10} respectively. In normal operation these leakage resistances W_9 and W_{10} must equal infinity as already mentioned.

Substituting the values of the general operators into the equations for the correction terms we obtain the corresponding complex values of $\bar{k}_1$ and $\bar{k}_2$ equations (10) and (11)

$$\bar{k}_1 = \frac{\left\{\Phi\left[1+\frac{C_9}{C_1}(1+m_1)\right]-\frac{Q}{W_9}\phi_7(1+m_1)+\psi_1\left[1+\frac{Q}{W_9}(1+m_1)\right]\right\} - j\left\{1+\frac{Q}{W_9}(1+m_1)+\Phi\,\phi_7\left[1+\frac{C_9}{C_1}(1+m_1)\right]-\frac{C_9}{C_1}\Phi\,\psi_1(1+m_1)\right\}}{\left\{\Phi\left[1+\frac{C_9}{C_1}(1+m_1)\right]-\frac{Q}{W_9}\phi_7(1+m_1)+\psi_1\left[1+\frac{Q}{W_9}(1+m_1)\right]\right\} - \left\{\frac{Q}{W_9}(\phi_9-\phi_7)\right\} - j\left\{1+\frac{Q}{W_9}(1+m_1)+\Phi\,\phi_7\left[1+\frac{C_9}{C_1}(1+m_1)\right]-\frac{C_9}{C_1}\Phi\,\psi_1(1+m_1)\right\} - j\left\{\frac{C_9}{C_1}\Phi(\phi_9-\phi_7)\right\}} \tag{10}$$

$$\bar{k}_2 = \frac{\left\{\Phi\left[1+\frac{C_{10}}{C_2}(1+m_2)\right]-\frac{S}{W_{10}}\phi_8(1+m_2)\right\} - \left\{\frac{S}{W_{10}}(\phi_9-\phi_8)\right\} - j\left\{1+\frac{S}{W_{10}}(1+m_2)+\Phi\,\phi_8\left[1+\frac{C_{10}}{C_2}(1+m_2)\right]\right\} - j\left\{\frac{C_{10}}{C_2}\Phi(\phi_9-\phi_8)\right\}}{\left\{\Phi\left[1+\frac{C_{10}}{C_2}(1+m_2)\right]-\frac{S}{W_{10}}\phi_8(1+m_2)\right\} - j\left\{1+\frac{S}{W_{10}}(1+m_2)+\Phi\,\phi_8\left[1+\frac{C_{10}}{C_2}(1+m_2)\right]\right\}} \tag{11}$$

In equations (10) and (11) the term expressed by Φ is

$$\Phi = \omega C_2 S = \omega C_1 Q$$

A study of the expressions for the correction terms shows that the majority of the terms in the numerators and denominators are alike. They differ, however, only in certain terms in both their real and imaginary parts.

These complex expressions for k_1 and k_2 are, therefore, of the general form

$$\bar{k}_1 = \frac{\alpha_1 - j\beta_1}{(\alpha_1 - \gamma_1) - j(\beta_1 + \delta_1)} \tag{12}$$

and

$$\bar{k}_2 = \frac{(\alpha_2 - \gamma_2) - j(\beta_2 + \delta_2)}{\alpha_2 - j\beta_2} \tag{13}$$

Where the α terms denote those that are alike in their real parts in both the numerators and denominators and the β terms apply to those imaginary terms in the respective numerators and denominators that correspond. The γ and δ terms in (12) and (13) include only those terms by which the respective numerators and denominators differ.

The absolute values and the phase angles of the correction terms introduced by shielding and guarding the bridge may be expressed as follows:

$$K_1 = \sqrt{\frac{\alpha_1^2 + \beta_1^2}{(\alpha_1 - \gamma_1)^2 + (\beta_1 + \delta_1)^2}} \tag{14}$$

$$K_2 = \sqrt{\frac{(\alpha_2 - \gamma_2)^2 + (\beta_2 + \delta_2)^2}{\alpha_2^2 + \beta_2^2}} \tag{15}$$

and

$$\phi_{K1} = + \frac{\alpha_1 \delta_1 + \beta_1 \gamma_1}{\alpha_1^2 + \beta_1^2 - \alpha_1 \gamma_1 + \beta_1 \delta_1} \tag{16}$$

$$\phi_{K2} = - \frac{\alpha_2 \delta_2 + \beta_2 \gamma_2}{\alpha_2^2 + \beta_2^2 - \alpha_2 \gamma_2 + \beta_2 \delta_2} \tag{17}$$

Taking into account the phase angles of the correction terms, we may write the generalized expression (8) for the power factor of the specimen as follows:

$$\psi_1 = \omega C_s S - \omega C_q Q - (\phi_{K1} + \phi_{K2}) \tag{18}$$

Analysis of the Correction Terms

In the analysis of the correction terms four cases that involve the accuracy and method of operation of the bridge are discussed.

Case 1

Case 1 considers the effect of failure to balance the guard circuits for phase. It belongs to the normal operation of the bridge in which the guard circuits are balanced for magnitude only, and the leakage resistances W_9 and W_{10} are assumed equal to infinity. In this case the normal operators are the general operators given in equation (9) with the exceptions of $\bar{a}_9$ and $\bar{a}_{10}$, which here become:

$$\bar{a}_9 = -\frac{j}{\omega C_9}$$

$$\bar{a}_{10} = -\frac{j}{\omega C_{10}}$$

Case 2

Case 2 considers the phase angle error introduced by the failure to balance the guard circuits for magnitude as well as phase, provided that the leakage resistances W_9 and W_{10} still remain infinite. Let θ_7 represent the ratio of the actual value of guard resistance R_7 to the proper value for correct magnitude balance, that is:

$$\theta_7 = \frac{R_7}{m_1 Q}$$

Similarly $$\theta_8 = \frac{R_8}{m_2 S}$$

Then, the conditions expressed under this case modify the general operators as follows:

$$\bar{a}_7 = \theta_7 m_1 Q (1 - j \phi_7) \qquad \bar{a}_9 = -\frac{j}{\omega C_9}$$

$$\bar{a}_8 = \theta_8 m_2 S (1 - j \phi_8) \qquad \bar{a}_{10} = -\frac{j}{\omega C_{10}}$$

in which θ_7 and θ_8 obviously become unity when the guard circuits are properly balanced for magnitude.

TABLE II

Case	a_7	a_9	α_1	β_1
1	$m_1 Q (1 - j \phi_7)$	$-\frac{j}{\omega C_9}$	$\Phi \left[1 + \frac{C_9}{C_1} (1 + m_1) \right] + \Psi_1$	1
2	$\theta_7 m_1 Q (1 - j\phi_7)$	$-\frac{j}{\omega C_9}$	$\theta_7 \Phi \left[1 + \frac{C_9}{C_1} (1 + m_1) \right] + \Psi_1$	1
3	$m_1 Q (1 - j \phi_7)$	$\frac{1}{\frac{1}{W_9} + j \omega C_9}$	$\Phi \left[1 + \frac{C_9}{C_1} (1 + m_1) \right] - \frac{Q}{W_9} \phi_7 (1 + m_1) + \Psi_1 \left[1 + \frac{Q}{W_9} (1 + m_1) \right]$	$1 + \frac{Q}{W_9} (1 + m_1)$
4	$\theta_7 m_1 Q (1 - j \phi_7)$	0	$-\phi_7$	1

Case	a_8	a_{10}	α_2	β_2
1	$m_2 S (1 - j \phi_8)$	$-\frac{j}{\omega C_{10}}$	$\Phi \left[1 + \frac{C_{10}}{C_2} (1 + m_2) \right]$	1
2	$\theta_8 m_2 S (1 - j \phi_8)$	$-\frac{j}{\omega C_{10}}$	$\theta_8 \Phi \left[1 + \frac{C_{10}}{C_2} (1 + m_2) \right]$	1
3	$m_2 S (1 - j \phi_8)$	$\frac{1}{\frac{1}{W_{10}} + j \omega C_{10}}$	$\Phi \left[1 + \frac{C_{10}}{C_2} (1 + m_2) \right] - \frac{S}{W_{10}} \phi_8 (1 + m_2)$	$1 + \frac{S}{W_{10}} (1 + m_2)$
4	$\theta_8 m_2 S (1 - j \phi_8)$	0	$-\phi_8$	1

Case 3

Case 3 considers the phase angle error introduced by the presence of leakage resistances W_9 and W_{10} in the capacitances C_9 and C_{10}, between the measuring circuits and their guards, provided that the guard resistances have the proper value for magnitude balance. In this case, the general operators of equation (9) hold.

Case 4

Case 4 considers the conditions and ratio errors that exist when the corners of the bridge are connected together, *i. e.*, A to A', as is customary in balancing the guard resistances R_7 and R_8 (See Operation). Under these conditions the operators involved become:

$$\bar{a}_7 = \theta_7 m_1 Q (1 - j \phi_7)$$
$$\bar{a}_8 = \theta_8 m_2 S (1 - j \phi_8)$$
$$\bar{a}_9 = 0$$
$$\bar{a}_{10} = 0$$

To obtain the phase angle and ratio errors produced by the conditions as outlined in these four cases, substitute the corresponding operators in the expressions for $\bar{k}_1$ and $\bar{k}_2$ (5) and determine the respective values of α, β, γ and δ terms (12) to (17) inclusive for each case.

Table II below gives for the four cases the values of the phase angle and ratio errors, together with the modifying operators causing the errors, and the corresponding expressions for the α, β, γ, and δ terms. In working out the values shown in this table the results

were simplified by neglecting the product of two phase angles when added to or subtracted from unity.

In most cases this entails an approximation of less than one part in 10,000 of the factor involved, and is, therefore, fully warranted since it means an approximation in the phase angle relation of the bridge of the order of one part in one hundred million.

Experimental Verification of Equations

Case 1

A study of the phase angle and absolute value errors, Table II, shows that the failure to balance the guard circuits for phase causes no error in the ratio balance since K_1 and K_2 here equal unity, and only a negligible phase angle error.

TABLE II

γ_1	δ_1	K_1	ϕ_{k1}
0	$\frac{C_9}{C_1}\Phi(\phi_q - \phi_7)$	1	$+\frac{C_9}{C_1}\left[1 + \frac{C_9}{C_1}(1 + m_1)\right]\Phi^2(\phi_q - \phi_7)$
$\frac{C_9}{C_1}\Phi(\theta_7 - 1)$	$\frac{C_9}{C_1}\Phi(\phi_q - \theta_7\phi_7) + \frac{C_9}{C_1}\Phi\Psi_1(\theta_7 - 1)$	1	$+\frac{C_9}{C_1}\Phi(\theta_7 - 1)$
$\frac{Q}{W_9}(\phi_q - \phi_7)$	$\frac{C_9}{C_1}\Phi(\phi_q - \phi_7)$	1	$+\frac{(\phi_q - \phi_7)}{\frac{W_9}{Q} + (1 + m_1)}$
$\frac{(\phi_q - \theta_7\phi_7)}{\theta_7(1 + m_1)}$	$-\frac{(\theta_7 - 1)}{\theta_7(1 + m_1)}$	$\frac{\theta_7(1 + m_1)}{(1 + 2m_1\theta_7 + m_1^2\theta_7^2)^{\frac{1}{2}}}$	$+\frac{(\phi_q - \phi_7)}{1 + \theta_7 m_1}$
γ_2	δ_2	K_2	ϕ_{k2}
0	$\frac{C_{10}}{C_2}\Phi(\phi_s - \phi_8)$	1	$-\frac{C_{10}}{C_2}\left[1 + \frac{C_{10}}{C_2}(1 + m_2)\right]\Phi^2(\phi_s - \phi_8)$
$\frac{C_{10}}{C_2}\Phi(\theta_8 - 1)$	$\frac{C_{10}}{C_2}\Phi(\phi_s - \theta_8\phi_8)$	1	$-\frac{C_{10}}{C_2}\Phi(\theta_8 - 1)$
$\frac{S}{W_{10}}(\phi_s - \phi_8)$	$\frac{C_{10}}{C_2}\Phi(\phi_s - \phi_8)$	1	$-\frac{(\phi_s - \phi_8)}{\frac{W_{10}}{S} + (1 + m_2)}$
$\frac{(\phi_s - \theta_8\phi_8)}{\theta_8(1 + m_2)}$	$-\frac{(\theta_8 - 1)}{\theta_8(1 + m_2)}$	$\frac{(1 + 2m_2\theta_8 + m_2^2\theta_8^2)^{\frac{1}{2}}}{\theta_8(1 + m_2)}$	$-\frac{(\phi_s - \phi_8)}{1 + \theta_8 m_2}$

The latter is shown to be true in the following typical numerical example of the measurement of the power factor at 500 volts 60 cycles of an impregnated paper specimen at 30 deg. cent. Complete data are given below.

Standard Air Capacitor	Specimen
$C_2 = 1110 \times 10^{-12}$ farad	$C_1 = 1159 \times 10^{-12}$ farad
$C_s = 2815 \times 10^{-12}$ farad	$C_q = 889 \times 10^{-12}$ farad
$C_{10} = 489 \times 10^{-12}$ farad	$C_9 = 469 \times 10^{-12}$ farad
$R_8 = 9909$ ohms	$R_7 = 8216$ ohms
$S = 5219$ ohms	$Q = 5000$ ohms
$m_2 = R_8/S = 1.899$	$m_1 = R_7/Q = 1.643$
$\phi_s = \omega C_s S = 0.00554$	$\phi_q = \omega C_q Q = 0.00168$

$$\Phi = \omega C_1 Q = \omega C_2 S = 0.00218$$

$$\psi_1 = \omega C_s S - \omega C_q Q = 0.00386$$

Substituting the proper values in the expressions for ϕ_{K1} and ϕ_{K2} of Case 1, Table II, and assuming as an extreme case that ϕ_7 and ϕ_8 are zero, the following phase angle errors are obtained:

$$\phi_{K1} = +\ 6.7 \times 10^{-9}$$

$$\phi_{K2} = -\ 26.3 \times 10^{-9}$$

These are seen to be negligible when compared with the phase angle sensitivity of our bridge $\pm 5 \times 10^{-6}$.

This numerical example is only one of many that could be presented and fully justifies our method of operating the bridge in which no attempt is made to balance the guard circuit for phase. It might also be stated in further justification of our practise that the capacitances to earth of the shields which are in parallel with R_7 and R_8, respectively, serve to reduce this error still further.

Case 2

In Case 2 where the guards are not properly balanced for either phase or magnitude it is evident that the absolute values of K_1 and K_2 are again unity and that ratio errors are absent.

It may be seen from Table II, Case 2, that the phase angle errors ϕ_{K1} and ϕ_{K2} are linear functions of the magnitude unbalance factors θ_7 and θ_8. To verify these equations experimentally the following test was made:

The bridge was balanced normally as in the numerical example given under Case 1, keeping the air capacitor

side of the bridge properly balanced for magnitude, we determined the value of ϕ_{K1} corresponding to different values of the guard resistance, R_7. The ratio, θ_7, of the actual value of the guard resistance to its true value was varied from zero to two. The results are given in Fig. 4 and it is evident that a linear relation exists between ϕ_{K1} and θ_7.

As a further check a similar test was performed to determine the value of ϕ_{K2} when θ_8 was varied, keeping

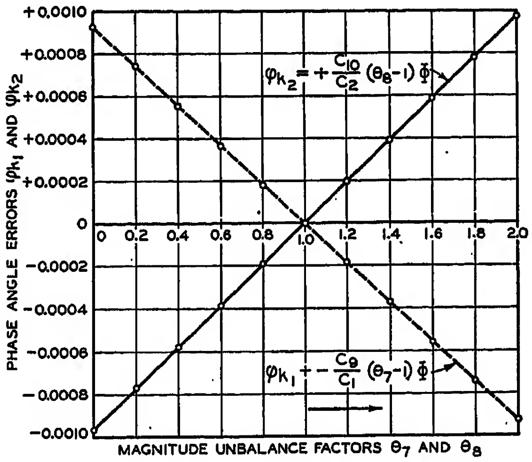

FIG. 4—EXPERIMENTAL VERIFICATION OF CASE 2

θ_7 equal to unity. The results of this run are also plotted in Fig. 4 and we again obtain linear relation between the two quantities.

Obviously, from such experimentally determined curves it is possible to compute the values of the cross-capacitances C_9 and C_{10}.

As a verification of these relations, the cross-capacitances, C_9 and C_{10}, were measured separately using a 1,000-cycle capacitance bridge. The results given below in Table III show a good agreement and serve further to prove the correctness of the equations.

TABLE III—COMPARISON OF CALCULATED AND MEASURED VALUES FOR THE CROSS-CAPACITANCES C_9 AND C_{10}

Capacitance	Capacitance computed from Fig. 4	Capacitance measured at 1,000 cycles
C_9	.469	.478
C_{10}	.489	.472

It is clearly evident from the equations that the phase angles errors are reduced by keeping C_9 and C_{10} small. The experimental results of Case 2 verify the mathematical relation and also show the importance of accurately balancing the guard resistances for magnitude.

Case 3

This case considers the phase angle errors caused by lack of phase angle balance in the guard circuits acting through the presence of leakage resistances W_9 and W_{10}. As in the two preceding cases, the ratio balance still remains unaffected when the guards are properly balanced for magnitude. The following test was performed to obtain experimental verification of the equations involved; Table II, Case 3:

1. The bridge was balanced in the normal way, with W_9 and W_{10} equal to infinity, the air capacitor was adjusted to one to one ratio with the specimen to within five ohms in 5,000, and the guard capacitance C_6 was varied to make the ratios m_1 and m_2 equal to each other to within 0.1 per cent.

2. The specimen guard circuit was then balanced for phase as well as magnitude using an additional variable capacitor in parallel with R_7.

3. An inductance L_8, of approximately 0.5 henry, was introduced in series with the air capacitor guard resistance R_8, and this resistance was decreased by an amount equal to the resistance of the inductance coil, thus preserving the magnitude balance but greatly increasing the phase difference $(\phi_s - \phi_8)$. It must be noted here that the insertion of L_8 giving the arm R_8 a large inductive phase angle caused no measurable power factor error when the guard of the air capacitor was balanced for magnitude only and not for phase.

4. The actual test was then performed, introducing the resistances W_9 and W_{10} which were kept at all times equal to each other, and which were varied from 100,000 ohms to zero, determining at each step the phase angle error caused by the phase angle difference $(\phi_s - \phi_8)$.

In this test it was necessary to keep W_9 equal to W_{10} to preserve the one to one ratio throughout, thereby eliminating errors due to residual angles in the resistance

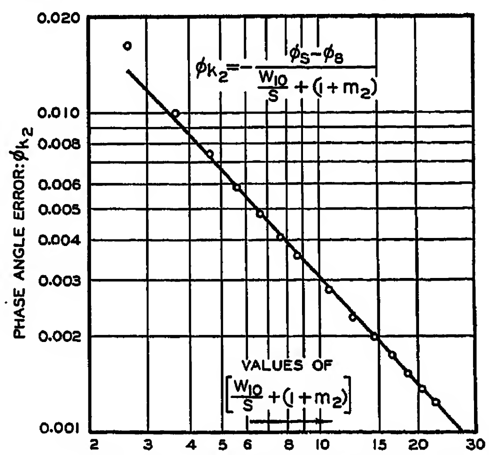

FIG. 5—EXPERIMENTAL VERIFICATION OF CASE 3

boxes. It was, therefore, necessary to balance the specimen guard circuit for phase as well as magnitude to confine the error studied to the phase difference $(\phi_s - \phi_8)$ alone, and it was deemed advisable to introduce an inductance in guard resistance R_8 to accentuate the error and make its measurement more accurate.

The phase angle error under consideration is

$$\phi_{K2} = \frac{\phi_s - \phi_8}{\frac{W_{10}}{S} + (1 + m_2)} \tag{19}$$

which may be written in the form

$$\log\phi_{K2} = \log(\phi_s - \phi_8) - \log\left[\frac{W_{10}}{S} + (1+m_2)\right] \quad (20)$$

It is readily seen from (20) that plotting in logarithmic coordinates the phase angle error ϕ_{K2} against the variable

$$\left[\frac{W_{10}}{S} + (1 + m_2)\right]$$

gives a straight line of which the slope is unity for axes of equal moduli. The results of experiment are plotted in Fig. 5 which shows a remarkable agreement between the results of experiment and the above theoretical considerations. It is interesting to note that ϕ_7 and ϕ_8 may be obtained by this test if desired.

Case 4

This case is of importance because it represents the conditions pertaining to the balancing of the guard circuits as described under operation. It considers the ratio error introduced by a given unbalance in the guard circuit acting through a short circuit between the measuring circuit and its guard.

As stated under the operation of the bridge, all four low-voltage arms R_7, Q, S, and R_8 are set at some tentative values, and the operator adjusts Q and S to obtain the preliminary ratio balance. We will confine our attention to the specimen side of the bridge and assume that the preliminary ratio balance is obtained with the tentative guard resistance R_7 off from its correct value by a magnitude unbalance, factor θ_7. Under these conditions the ratio error caused by short-circuiting $B - B'$ is

$$K_1 = \frac{\theta_7 (1 + m_1)}{\sqrt{1 + 2\, m_1\, \theta_7 + m_1^2\, \theta_7^2}} = \frac{\theta_7 (1 + m_1)}{1 + m_1 \cdot \theta_7} \quad (21)$$

This unbalance in ratio results in a deflection of the galvanometer. Obviously from equation (21), when θ_7 is made equal to one, K_1 becomes unity and the ratio error disappears. In operating the bridge the guard resistance R_7 is varied until the ratio unbalance disappears as already explained. Under these conditions

$$\frac{R_7}{Q} = \frac{C_1}{C_5} = m_1$$

Similarly when the air capacitor side of the bridge is adjusted K_2 equals 1 and

$$\frac{R_8}{S} = \frac{C_2}{C_6} = m_2$$

From the analysis of this case it is evident that our method of adjusting the guard resistance without disturbing in any way the main galvanometer connection is fully justified.

CONCLUSIONS

The conclusions may be summarized as follows:

1. In a completely guarded and shielded bridge it is advisable to keep the cross-capacitances existing between the measuring circuits and the guard circuits low.
2. In such a bridge it is of prime importance that the conductances of the cross-capacitances be maintained at zero.
3. We have developed a method employing a separately excited moving coil a-c. galvanometer that makes it possible to balance the guard circuits using the main galvanometer as a detector, without disturbing the connections of the main galvanometer in any way.
4. The equations for the correction terms introduced by the shielding and guarding system are developed and their values are determined for the constants of our bridge.
5. We have shown by both mathematical and experimental proofs that the error introduced in our bridge by failure to balance the guards for phase angle is negligible.

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Discussion

Leo J. Berberich: For some years, engineers interested in power factor measurements on insulating materials at high voltages and commercial frequencies have felt the need for some suitable means of verifying the accuracy of such measurements. As a result of this, several methods for checking dielectric loss measuring equipment have been proposed in the last two or three years. Some of these are thermal methods utilizing temperature rise associated with power loss, and others involve the use of a standard load usually constructed of glass. These have met with some degree of success, as the literature reveals, but leave something to be desired when it comes to verifying measurements of the small power factors found in good quality insulating oils.

A little over a year ago work was begun on the development of a new "standard of low power factor" at the Johns Hopkins University. This standard has recently been completed and a paper by Dr. Kouwenhoven and myself is now in the hands of the Instruments and Measurements Committee of the Institute. I might say briefly that it consists of a well-shielded and guarded compressed air capacitor and very specially shielded resistors. The standard can be used for voltages as high as 25 kv. and its power factor can be computed accurately. During the course of its development I have had occasion to check the accuracy of the bridge described by Dr. Kouwenhoven as well as that of another bridge similarly constructed. The following table gives an idea of the excellent agreement found between the computed power factor of the standard and the power factor as measured by the bridges:

COMPUTED POWER FACTOR OF STANDARD *vs.* MEASURED POWER FACTOR

Computed power factor 60 cycles	Measured power factor Bridge No. 1	Measured power factor Bridge No. 2
0.000195	0.000196	0.000194
0.000996	0.000992	0.000996
0.001993	0.001983	0.001993

The data listed in the table not only give further evidence as to the accuracy of the bridge described in the paper by Dr. Kouwenhoven and Mr. Baños, but also show that the two bridges used at Johns Hopkins for measurements on insulating oils agree remarkably well. The small deviations from the computed power factor of the standard were due to the fact that the limits of sensitivity of the bridges were approached.

J. C. Balsbaugh: In the bridge described in the paper by Messrs. Kouwenhoven and Baños the power factor ψ_1 of the specimen is given as

$$\psi_1 = \omega C_3 S - \omega C_q Q$$

This assumes that the absolute power factor of the air condensers is equal to zero. In general, any bridge used for the measurement of the power factor of dielectrics measures the difference in the power factors of the condensers forming the high-tension arms of the bridge. The use of a substitution method in measuring the power factor of a sample will not eliminate the absolute power factors of the air condensers, but will give the difference in the power factors of the sample and the air condenser it replaces. Thus in the measurement of the power factors of dielectrics to a given precision, it is first necessary to investigate the absolute power factors of the condensers to be used in the bridge and determine if these absolute power factors are of the magnitude of the desired power factor precision.

A modified Schering bridge with a precision in power factor measurement of 10^{-6} has been constructed at the Massachusetts Institute of Technology in connection with research carried on in cooperation with the Cable Research Subcommittee of the National Electric Light Association. A paper describing this bridge was presented at the meeting of the Committee on Electrical Insulation of the National Research Council in Cambridge, Mass., November 13, 1931. Progress reports covering the design, construction, and operation of this bridge have also been submitted to the Cable Research Subcommittee of the National Electric Light Association. It is planned to make formal publication of this research when all the factors affecting the power factor precision of the bridge have been fully investigated. This bridge has a sensitivity such that a change in power factor very much lower than 10^{-6}, and a capacitance difference materially lower than 10^{-6} of the high-tension capacitances are detectable. Tests with this bridge have shown that air condensers may have an absolute power factor of the order of 10^{-5}. A study of the probable causes of this power factor has shown that it is not due to conduction currents in the gas, a loss in the solid dielectric between the bridge and shield surfaces, or to extraneous matter on the plates of condensers. A number of tests has shown that the loss depends on the type of metal used in the condenser conducting surfaces, the voltage gradient, surface area, and apparently is due to the gas adsorbed on the condenser surfaces.

In using a substitution method for measuring the power factor of a sample it is essential that the resistances in the low-tension arms be maintained constant in the two balances. The use of a substitution method primarily eliminates the shunt capacitance to ground of the low-tension arms and thereby permits obtaining the power factor of the sample in terms of the difference in capacitances in the two balances of one condenser in the low-tension arms. However, if the low-tension resistances are adjusted in the two balances the shunt capacitances to ground in the resistances are changed. Therefore the measured power factor will not be given in terms of the differences between the settings of one low-tension capacitance. In the bridge at the Massachusetts Institute of Technology previously referred to, variable condensers are used in one of the high-tension arms. Thus a capacitance balance of the bridge may be obtained entirely by an adjustment of the high-tension condensers with the low-tension resistances maintained constant. In this manner it is possible to eliminate completely the shunt capacitances of the bridge to ground from causing an error in the power factor measured by the bridge. The variable capacitances used in this bridge permit obtaining as accurate a capacitance balance as a power-factor balance. These variable condensers are designed with concentric cones that may be moved axially relative to each other. By this method it is possible to obtain and detect changes in capacitances less than 10^{-5} $\mu\mu$f. (10^{-17} farads).

In general, the effect of a phase unbalance in the shield voltage will not cause an error in the power factor measured by the bridge described in this paper. This assumes that the phase shifter is quite accurately set. The effect of a phase unbalance in the shield voltage will be to give an incorrect capacitance balance of the bridge. In the study of dielectrics having very low power factor it is advisable to be able to detect and measure changes in capacitance of the sample of the same order as the power factor. The study of both capacitances and power factor change should permit a clearer and more definite analysis of the results of a test. The magnitude of the phase unbalance of the shield voltage depends principally upon the relative values of capacitances from high-tension to shield and to bridge, and capacitances from shield and bridge to ground. In the usual bridge these values are such that phase balance of the shield is necessary to give a satisfactory bridge capacitance balance where high precision is necessary.

In the bridge described in this paper the shield is balanced by directly connecting the bridge and shield. This method requires two separate shield circuits and thereby requires considerable adjustment to get an accurate shield balance. It would seem preferable to have one shield circuit and balance by connecting the detecting apparatus between the bridge and shield circuit. This method may be accomplished quite easily and will permit a high accuracy in the shield balance.

In this paper there are no calculations or tests giving the sensitivity or precision of the bridge. Furthermore it should be noted that precision in power factor measurement may be very much different from the sensitivity of the bridge to changes in power factor. In general, the precision in power factor measurements is much more important than the bridge sensitivity.

S. K. Waldorf: For Case I it is shown experimentally that the phase angle errors ϕ_{k1} amd ϕ_{k2} in Table II are negligible with specimens having a capacitance of about 1,100 $\mu\mu$f. The authors mention having measured other specimens having capacitances as low as 40 $\mu\mu$f., for which the ratios C_9/C_1 and C_{10}/C_2 become of the order of 30 instead of about ½ for the case given. At the same time there is the corresponding decrease in Φ which enters as a quadratic in expressions for ϕ_{k1} and ϕ_{k2}. The net effect of reduction of specimen size is, then, that the values of these correction terms are not appreciably changed, other factors being equal.

However, to maintain the bridge sensitivity unimpaired, the values of S and Q must be increased, resulting in increases in ϕ_{k1} and ϕ_{k2} which can become appreciable in such circumstances. For the condition to hold that the net correction remain negligible, it then becomes of some importance that the bridge be symmetrical in order for ϕ_{k1} to be very nearly equal numerically to ϕ_{k2}, as the latter quantity is shown to be negative in Table II.

The condition considered in Case III is of practical importance, as it is a very real source of difficulty in humid weather. In such weather there is condensation of moisture on the insulation of the bridge which causes appreciable values of leakage conductance between circuits. The values of W_9 and W_{10}, instead of being

nominally equal to infinity as desired, become finite, indeterminate, and variable quantities, making evaluation of ϕ_{k1} and ϕ_{k2} impossible. To a certain extent these troublesome effects can be eliminated, or at least minimized in very bad weather, by coating the insulation with paraffin and by having a minimum of contact surface between the insulation and the conductors. From the very erratic nature of such difficulties due to humidity, it is easily understandable that no method of correction has yet been devised. Indeed, on some summer days of high humidity, conditions become so unsteady that measurements are impossible. This may seem strange to the uninitiated, but is quite common experience for those making refined dielectric measurements of any sort.

Fig. 2 of the galvanometer circuit shows double shielding on the transformer. Such transformers are not in common use nor easily obtained. I believe it would be of value if the authors could tell us briefly the purpose of such shielding and if it is essential, as perfect double shielding with a high value of insulation resistance is not readily made in a compact assembly, and hence is relatively expensive to manufacture.

In conclusion, I should like to add a practical word of precaution for those who may be called upon to build small high-voltage air capacitors for such service as the authors describe. The natural tendency is to make the plates as small as possible for compactness and economy, resulting in small spacings of about 2 mm. or less. Close spacings usually are the source of much trouble and annoyance arising from small fibers bridging the gap between plates and causing either flashover or a power factor in the air capacitor. A much more satisfactory arrangement has been found with plate dimensions large enough to allow a spacing of not less than about 5 mm. for the desired value of capacitance, which is quite effective as a preventative of such bridging.

Perry A. Borden: The method of balancing out induced voltages in the galvanometer coil by the use of a mutual inductance in the field circuit appears to remove one of the objectionable features of the electrodynamic galvanometer. It has been found that by the use of two quadrature reference voltages derived from the secondary of the phase-shifting transformer as shown in Fig. 1, and applied alternately to the field coil of the galvanometer as the length and position respectively of the current vector in the bridge circuit are reduced, much time in balancing such a circuit may be saved.

Another very satisfactory method of detecting a balance condition* consists in exciting the galvanometer field from a frequency differing slightly from that of the system upon which the tests are being made, and proceeding with the balancing process until the "beat" oscillations disappear.

R. P. Siskind: In their conclusions; Messrs. Kouwenhoven and Baños state that it is of prime importance that the conductance of the cross-capacitances between the main electrodes with their leads and their guards be maintained at zero. Under this condition, it is shown analytically and experimentally that failure to balance the guards for phase angle introduces negligible error. In this connection, the authors state that it is essential for accurate measurement that the insulation resistances of these cross-capacitances, as measured by a megger, be maintained at infinity. Since this is an a-c. bridge and these cross-capacitances contain dielectric material, their a-c. leakage resistances cannot be infinite but will have values equal to the equivalent parallel resistances of these cross-capacitances at the test frequency. These values will then depend upon the power factors of the cross-capacitances. However, a rough calculation based upon the values given under the heading, "Experimental Verification of Equations" shows that at 60 cycles, an assumed power factor of 0.100 for C_{10} would give W_{10} a value of 54 megohms and, although finite, this value of W_{10} would lead to an error in measured power factor somewhat less than the accuracy claimed by the authors. According to the equations, the error would be entirely negligible for a more reasonable value of power factor of C_{10}.

Another item worthy of consideration is the possible effect upon the accuracy of the bridge of the presence of harmonics. The authors use a detecting device which operates upon the wattmeter principle. If the potential applied to the test specimen, C_1, is high enough to produce ionization, third and other harmonics will be produced in the current wave through C_1 even with the application to C_1 of a pure sine wave. This effect has been found in measurements with the Dawes-Hoover bridge upon dielectric specimens stressed beyond the ionization point. The bridge is generally out of balance for these harmonics when balanced for the fundamental and this results in the presence of harmonic voltages across the detector. The tuned vibration galvanometer is not affected. With the a-c. galvanometer used by the authors, the presence of third and other harmonic currents in the moving coil would give a deflection if any corresponding harmonic current were present in the field winding. It is hard to believe that the output of a phase-shifting transformer excited with a pure sine wave voltage is entirely free from harmonics. If corresponding harmonic currents of any appreciable magnitude do exist, a torque will be exerted upon the moving coil which would be offset by an equal and opposite torque produced by a slight unbalance of the bridge for the fundamental frequency in bringing the galvanometer deflection to zero. Thus the possibility of some small error does exist when ionization takes place in the test specimen.

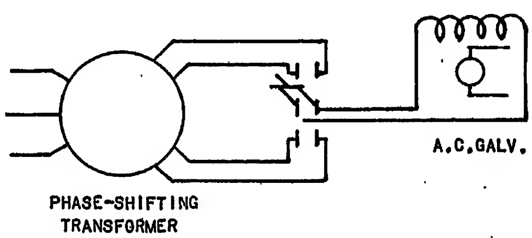

Fig. 1

W. B. Kouwenhoven and Alfredo Baños, Jr.: Mr. Balsbaugh states that we have assumed the absolute power factor of the air capacitor C_2 of the bridge to be zero. That this assumption is justifiable at 60 cycles is clearly brought out by an investigation conducted by one of the authors[1] of this paper and also by the work of Churcher and Dannant.[2]

Mr. Balsbaugh reports that his air capacitors have a power factor of the order of 10^{-5} which he believes is caused by the absorption of gas by the electrode surfaces. If such were the case it is quite possible that this power factor will also be associated with the test cell as well as with the air capacitor, and thus tend to neutralize each other in the bridge.

We have measured power factors of oil samples as low as 0.000025 and we have checked the accuracy of such measurements by a method that does not involve either the standard air capacitor or the Schering bridge. This method is fully described in a paper by one of the authors.[3] Briefly, it consists of the calculation of the power factor of the sample at 60 cycles from the charge and discharge current time relations under continuous potentials. Thus it appears that in measuring power factor of this order an error of 10^{-5} in the power factor of the air capacitor

Balance Methods in A-C. Measurement, P. A. Borden, Trans. A.I.E.E., XLII, (1923), p. 395.

1. *The Phase Defect Angle of an Air Capacitor*, W. B. Kouwenhoven and O. L. Lemmon, Trans. A.I.E.E., Vol. 49, July 1930, p. 952.

2. "The Use of Air Condensers as High-Voltage Standards," B. G. Churcher and C. Dannant, *Journal I.E.E.*, Vol. 69, No. A16, Aug. 1931.

3. *The Predetermination of the A-C. Behavior of Dielectrics.* J. B. Whitehead and A. Baños, Jr., A.I.E.E. Winter Convention, 1932.

would not permit the excellent agreement that is obtained between the power factor measured in the bridge and that computed from the d-c. characteristics.

The error in the ratio balance that is caused by failure to balance the guard circuits for phase is very small. In our operation of the bridge the ratio arms, Q and S, are only balanced to the nearest ohm in 5,000 and the above mentioned error is much less than this and can be safely neglected.

Our method of balancing the guards by connecting directly the bridge and the shield possesses the distinct advantage of permitting the use of the full sensitivity of the main detector without disturbing in any way its connections. In our bridges using no amplifiers this method has proven very simple and quick and gives accurate results. We recommend it strongly because of the small amount of auxiliary equipment and adjustment that is required.

As regards the precision of the bridge, the data presented by Dr. Berberich in his discussion covers this point fully.

The shielded transformer in the galvanometer circuit is used because it fixes accurately the distributed capacitance that exists between the arms of the bridge and the ground. The connection of this shield to the B corner of the bridge (Fig. 1 of the paper) places this capacitance in parallel with C_2. Unless a doubly shielded transformer is used and connected as shown the effect of this capacitance cannot be evaluated.

The suggestion of Mr. Borden is very interesting and we are at present testing that method of balancing in another research using a similar bridge.

The point raised by Mr. Siskind as to harmonics is of considerable importance. We made an oscillograph study of the currents through the different arms of our Schering bridge when supplied with current from a General Electric sine wave generator. In this work we used the amplifier oscillograph of Dr. Waldorf.[4] We measured the voltage induced by the galvanometer field in its moving coil and found it practically free from harmonics. We found evidence of a small tooth ripple in the currents through the arms of the bridge. These currents, however, were free from low order harmonics. We do not feel that harmonics cause any trouble in our bridge because of the excellent agreement that we have been able to obtain between calculated and measured power factors on the same sample. Furthermore our bridge is operated at potentials that are considerably below the ionization value.

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4. "The Amplifier Oscillograph Applied to the Study of Dielectrics with Continuous Potentials," S. K. Waldorf. Forth-coming paper through A.I.E.E.

Power Factor Measurement by the Capacitance Bridge

An Analysis of the Parallel Substitution Method as Applied to Two Types of Capacitance Bridges for Capacitance and Power Factor Measurements Upon Dielectric Specimens

BY ROBERT P. SISKIND*
Associate, A.I.E.E.

Introduction

SEVERAL types of capacitance bridges for measurement of the capacitance and the power factor of dielectric specimens are in use at the present time. Some of these bridges make a direct comparison between the capacitance under test and a standard capacitance. The Schering and Dawes-Hoover high-voltage power-frequency bridges are too well-known examples of this type. For accurate power factor measurements upon dielectric specimens at low voltages and audio frequencies a substitution method is generally preferred.

Two substitution methods are commonly employed. Using one method, here referred to as the "direct" substitution method, the test capacitance is first balanced in the bridge circuit against an auxiliary capacitance. The test capacitance is then removed, replaced by a variable standard capacitance, and the bridge rebalanced. In this way a comparison of the test and standard capacitance is obtained, and the power factor and capacitance of the former are determined if the power factor and capacitance of the latter are known at the particular setting used. Using the other method, here referred to as the "parallel" substitution method, the test capacitance and a variable standard capacitance in parallel are first balanced in the bridge circuit against an auxiliary capacitance. The test capacitance is then removed and the bridge rebalanced by variation of the standard capacitance. With this method it is necessary to know the capacitance and manner of variation of resistance with capacitance of the standard condenser used, but it is not necessary to know the actual values of its resistance or phase angle at the settings used.

Both methods are generally applicable to the capacitance bridges commercially available for these measurements upon small capacitances at low voltages and audio frequencies. With each method, the small change in phase angle of the arm of the bridge circuit in which the substitution is made must be counterbalanced in the second balance of the bridge. The compensation for this change in phase angle enters directly into the measurement of power factor of the test capacitance, and it is the manner of making this adjustment in which the bridges in common use show essential differences.

One manner of making this adjustment is the use of a variable resistance in parallel with the test and standard capacitances. The capacitance and conductance bridge of the Bell Telephone Laboratories[1] uses this arrangement. A second arrangement, used in the equal-arm capacitance bridge of the General Radio Company,[2] is a variable resistance in series with either the standard of auxiliary capacitances as the balances may require. A third device, used in the precision audio-frequency bridge of the Leeds & Northrup Company,[3] is a variable capacitance in parallel with one of the fixed resistance ratio arms of the bridge.

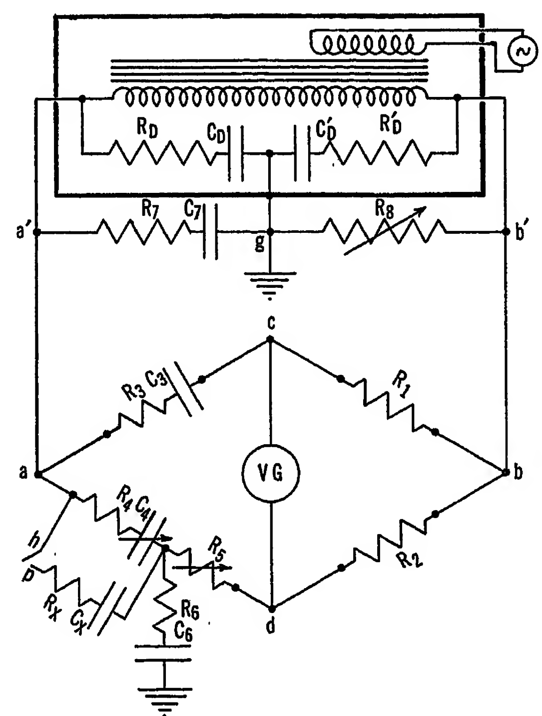

Fig. 1—High-Voltage Capacitance Bridge

This paper deals primarily with an analysis of the parallel substitution method applied to capacitance bridges employing the second and third arrangements mentioned in the preceding paragraph.

High-Voltage Capacitance Bridge Using the Parallel Substitution Method

First consider the substitution type of b idge shown in Fig. 1; R_1 and R_2 are equal fixed non-inductive resistances, C_3 is a low loss fixed condenser having an equiva-

*Instructor in Elec. Engg., Harvard Engineering School.

Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 25-29, 1932.

1. For references see end of paper.

lent series resistance R_3, C_4 is a precision variable condenser having an equivalent series resistance R_4 varying with the capacitance C_4, R_5 is a variable non-inductive resistance, and C_x is the capacitance of the dielectric specimen having an equivalent series resistance R_x. In the Wagner ground circuit, C_7 is a large fixed air condenser having an equivalent series resistance R_7, R_8 is a variable non-inductive resistance, and the distributed capacitances of the high-voltage winding of the transformer to the grounded case are represented by the capacitances C_D and C_D' having equivalent series resistances R_D and R_D'. For safety it is necessary to ground the transformer case.

The bridge is first balanced by adjustment of C_4 and R_5 with the lead h in contact at p thereby connecting the precision condenser and the test specimen in parallel.

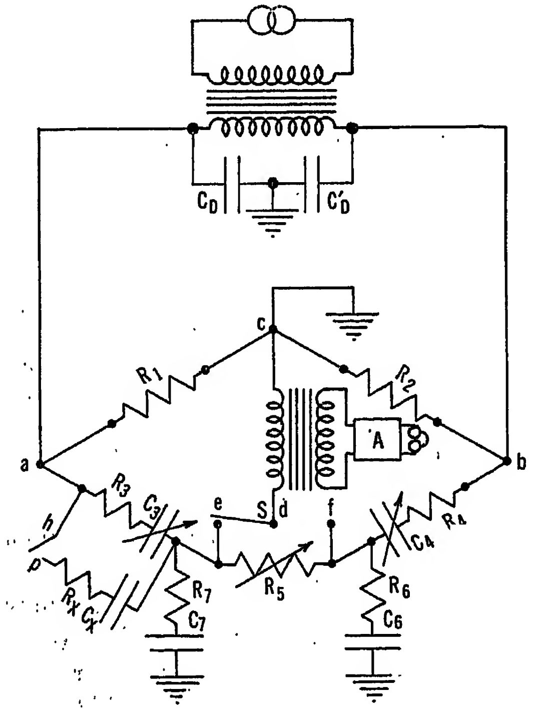

FIG. 2—AUDIO-FREQUENCY CAPACITANCE BRIDGE

The lead h is then just removed from contact at p and the bridge rebalanced by adjustment of C_4 and R_5.

A bridge of this type was constructed in 1923 for measurements up to 20 kv.

An early and persistent source of difficulty with this bridge was the impossibility of obtaining an accurate Wagner-ground balance. A study of Fig. 1 will show the reason. The condition for a perfect Wagner-ground balance with the vibration galvanometer connected to points cg is,

$$Z_{7D}/Z_3 = Z_{8D'}/R_1 \tag{1}$$

where Z_{7D} is the parallel impedance of C_D, C_7, and their equivalent series resistances; Z_3, the series impedance of bridge arm ac; $Z_{8D'}$ the parallel impedance of $C_{D'}$, its equivalent series resistance $R_{D'}$, and the resistance R_8; and R_1 the resistance of the arm cb.

C_3 is a fixed air condenser. Its dielectric material for supporting the high-voltage plate is in positions where the electrostatic field is weak. This makes the phase angle as small as possible. At first, three pyrex glass pillars were used as supports. Later this design was much improved by using a single solid support so placed that the dielectric is located in the electrostatic field between the high-voltage plate and the grounded shielding. This same construction was also used with the precision variable condenser C_4. Therefore, the condenser C_3 had a very low phase angle and R_3 was very small. The transformer was oil-filled, making the angles of defect of the dielectric in the distributed capacitances C_D and $C_{D'}$ very much larger than the angles of defect of the air condenser C_3. Increasing C_7 to an air capacitance of over 1,100 $\mu\mu$f. in an attempt to reduce the phase angle of Z_{7D} sufficiently to give a balance was unsuccessful. R_8 was about 3,000 ohms making the effect of the distributed capacitance $C_{D'}$ upon the phase angle of $Z_{8D'}$ very small. Hence, the net effect of the losses in the distributed capacitance of the transformer was to prevent a satisfactory Wagner-ground balance with this circuit. Subsequent study indicates that the insertion of a suitable variable self-inductance in series with the arm gb' would have made possible a perfect Wagner-ground balance in accordance with equation (1).

Also, it was found that the value of R_5 required for a bridge balance showed a surprisingly large variation with a small change in the adjustment of the Wagner-ground balance. In an effort to determine if the presence of the stray capacitance C_6 between the low potential side of the C_4 condenser case and the grounded shielding was responsible for this effect, a mathematical analysis of the bridge circuit was made including this capacitance. Because of its similarity to the analysis of the audio-frequency bridge with Wagner ground given in Appendix II, this derivation is not given.

This analysis yielded an astonishing result. It indicated that the presence of this stray capacitance had an entirely negligible effect upon the capacitance of the test specimen as measured by the bridge but resulted in a very serious error in the measured value of its equivalent series resistance and consequently its power factor. The solution showed that the value of R_x as measured must be multiplied by the factor $[1 + (C_6/C_{4'})]$ where C_4' is the capacitance of C_4 for the balance with lead h not in contact at p.

With the shielding in use at the time of this discovery, this correction factor had a value exceeding 2. C_6 was somewhat greater than C_4'. This meant that the measured power factors were less than 50 per cent of the true power factors. The shielding was then moved a considerable distance away from the cases of the condensers C_3 and C_4 considerably reducing this correction factor.

In view of the entirely satisfactory development of the Dawes-Hoover high-voltage bridge at that time and the ground balance and correction factor, difficulties en-

countered with this substitution bridge, it was finally abandoned as applied to high-voltage measurements.

A Low-Voltage Audio-Frequency Bridge Using the Parallel Substitution Method

The bridge circuit of Fig. 2 was later used in making power factor measurements at audio frequencies. It was found that a considerable variation in the measured value of R_x was obtained as different settings of the balancing condenser C_4 were used. This indicated the probability of the existence of a stray capacitance error similar to that found in the high-voltage bridge. The only essential difference between the circuits of Figs. 1 and 2 is the interchange of points of application of power input and detector, the circuit of Fig. 1 being preferable for high-voltage work and that of Fig. 2 for low voltages due to its symmetry.

It thus became advisable to derive the bridge equations taking into consideration the effect of the stray capacitance to ground C_6 of the metal case of the condenser C_4. This derivation is given in detail in Appendix II. With switch s on point e, it is shown that

$$C_X \doteqdot \Delta C_3 \tag{2}$$

$$R_X \doteqdot \Delta R_5 \, (C_3'/C_X)^2 \, (1 + [C_6/C_4]) \tag{3}$$

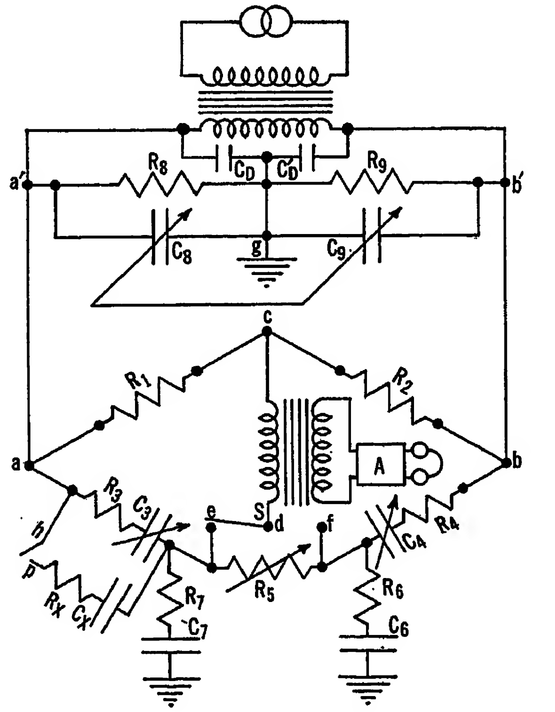

Fig. 3—Capacitance Bridge with Wagner Ground

where ΔC_3 is the change in capacitance of the precision condenser C_3 between the two bridge balances, with and without lead h in contact at p, ΔR_5 is the change in resistance of R_5 between the two bridge balances, and C_3' is the capacitance of C_3 for the balance with lead h not in contact.

In these balances, it is often necessary to have R_5 in arm db when balancing with lead h in contact and in arm ad when balancing with lead h not in contact. In this case, equation (7) becomes

$$R_X \doteqdot [R_5(1+\{C_6/C_4'\}) - R_5'(1+\{C_7/C_3'\})](C_3'/C_X)^2 \tag{4}$$

where R_5 and R_5' are values with lead h in contact and not in contact respectively. Obviously, with point e at ground potential, C_7 will have no effect on the balance, while with point f at ground potential the same will be true of C_6. Hence, only one of these stray capacitances can effect a single balance.

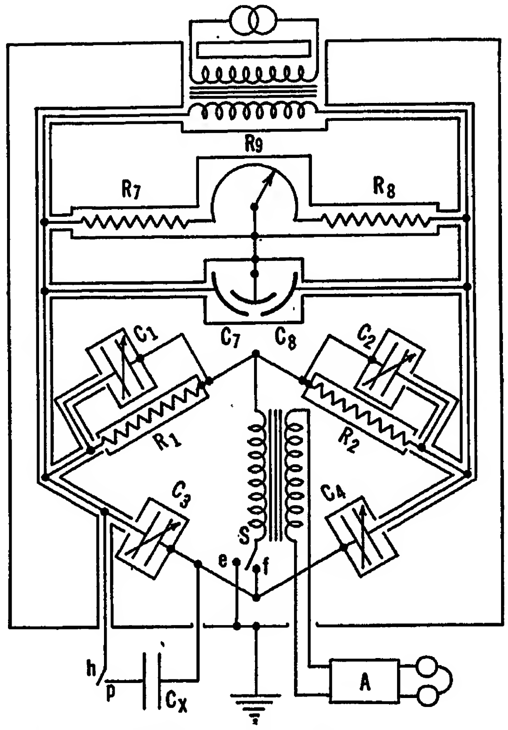

Fig. 4—Recommended Type of Capacitance Bridge

A suggestion that the ground should be removed to point d, Fig. 2 was made by Professor Robert F. Field, then of the Cruft Laboratory. He later caused this change to be made in a commercial instrument.[2] The derivation of the bridge equations for this ground position, given in Appendix II, shows that the error due to stray capacitance is practically eliminated.

Fig. 3 shows this capacitance bridge circuit using a Wagner-ground connection instead of a direct ground. In Appendix II, the equations for this bridge are shown to be identical with equations (6), (7), and (8). Therefore, the error and correction factor are not eliminated by the use of a Wagner ground connection.

A Recommended Low-Voltage Audio-Frequence Capacitance Bridge Using the Parallel Substitution Method

The capacitance bridge shown in Fig. 4 is essentially similar to the precision audio-frequency bridge of the Leeds & Northrup Company[3] with the addition of a Wagner-ground connection and the incorporation of both standard and auxiliary condensers into the bridge unit. Although less flexible, this single unit construc-

tion is advantageous when used for this particular type of measurement. No variable resistance is required other than that in the Wagner-ground connection. Since the rotor and shields of the four variable condensers are all brought to ground potential by the bridge and Wagner-ground balances, no stray capacitance error similar to that previously described exists.

In making a measurement, the auxiliary condenser C_4 is set at some convenient value of capacitance depending upon the capacitance C_x of the test specimen; lead h is placed in contact at p; and a balance is obtained with switch S on point f, by variation of the capacitance of the precision condenser C_3 and of the condensers C_1 and C_2. A Wagner-ground balance is then obtained with switch S on point e, after which switch S is returned to point f and a final bridge balance obtained. This three-step process is then repeated with lead h just removed from contact at p. The capacitance C_x and power ratio η_x, (ratio of resistance to reactance), of the test specimen are given by the equations:

$$C_X \doteq C_3' - C_3 \qquad (5)$$

$$\eta_X \doteq \omega\,[C_3'/C_X]\,[R_2\,(C_2 - C_2') - R_1\,(C_1 - C_1')] \qquad (6)$$

where the primes denote the capacitances of the condensers for the balance with lead h just removed from contact at p. The derivatives of (5) and (6) are given in Appendix III. Since R_1 and R_2 are equal in the construction of this bridge, these equations reduce to

$$C_X \doteq \Delta C_3 \qquad (7)$$

$$\eta_X \doteq \omega R_1\,(\Delta C_1 - \Delta C_2)\,(C_3'/C_X) \qquad (8)$$

where ΔC_1, ΔC_2, and ΔC_3, are the increases in the capacitances of these condensers for the second balance over their values for the first balance. Usually but one of the condensers C_1 and C_2 will need to be varied and either ΔC_1 or ΔC_2 will be zero.

If the power ratio η_x is low so that the tangent, (η_x), and sine of the phase angle of C_x are approximately equal, equation (8) gives the power factor directly. Otherwise the power factor is given by the equation:

$$(\text{power factor})_X = \sin\tan^{-1}\eta_X \qquad (9)$$

Conclusions

The form of capacitance bridge shown in Fig. 4 has the following advantages:

1. All operating controls are at ground potential reducing the effects of hand capacitance to a minimum.
2. The bridge is entirely self-contained except for oscillator, amplifier, and telephone receivers.
3. All parts are totally shielded except the high-potential terminal for the high-potential lead h to C_x.
4. All controls are continuously variable.
5. The bridge may be constructed entirely of standard parts, the shielding excepted.

Acknowledgment

The author wishes to acknowledge his indebtedness to Dean Harry E. Clifford and to Professor Chester L. Dawes of the Harvard Engineering School for their helpful suggestions in the preparation of this paper.

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Appendix I

Derivation of Equations for the Capacitance and Power Factor Measurement of Dielectric Specimens Using the Parallel Substitution Method and Bridge Circuit of Fig. 2

In Fig. 5 are shown the equivalent series circuit and the equivalent parallel circuit of an imperfect condenser. Since Z_P must equal Z_S, it is easily shown that

$$R_S - j\,(1/\omega C_S) = [R_P/(1 + R_P^2\omega^2 C_P^2)] - j\,[R_P^2\omega C_P/(1 + R_P^2\omega^2 C_P^2)] \qquad (10)$$

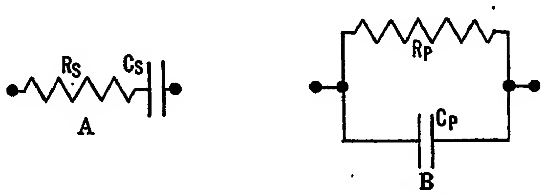

Fig. 5—Equivalent Series and Parallel Circuits of an Imperfect Condenser

The angle of defect of the condenser is given by

$$\theta = \tan^{-1}\,(1/R_P\omega C_P) \qquad (11)$$

If θ does not exceed 1 deg., $\tan\theta \leqq 0.0175$ and $R_P^2\omega^2 C_P^2 \geqq 3{,}260$. Therefore, $R_P^2\omega^2 C_P^2 >> 1$ and equation (10), to a degree of approximation equal to or better than 0.0306 per cent, gives

$$R_S \doteq 1/R_P\omega^2 C_P^2 \qquad (12)$$

$$C_S \doteq C_P \qquad (13)$$

The ratio of the equivalent series resistance to reactance of an imperfect condenser is defined as the power ratio, η_S.

$$\eta_S = R_S\omega C_S \qquad (14)$$

This is obviously equal to $\tan\theta$ where θ is the angle of defect of the condenser. If $\eta_S \leqq 0.1$, $\eta_S^2 \leqq 0.01 = 1/R_P^2\omega^2 C_P^2$. Then $R_P^2\omega^2 C_P^2 = 1/\eta_S^2 \geqq 100$, and the approximations of equations (12) and (13) are within 1 per cent. As will be seen from equation (10), the approximate value of R_S exceeds the true value by this percentage while the true value of C_S exceeds the approximate value by this percentage. The approximation in per cent is about $100\,\eta_S^2$.

With two imperfect condensers in parallel, each having a small angle of defect, the equivalent series resistance and capacitance of the combination may readily

be found. In Fig. 6, it is desired to find the constants of the equivalent series circuit shown in (D) to make it equivalent to the given circuit (A). This may be done to a high degree of approximation, by using equations (12), (13), and (14) and taking the two intermediate steps illustrated in (B) and (C).

$$R_{AP} \doteq 1/R_{AS}\omega^2C_{AS}^2 = 1/\eta_{AS}\omega C_{AS} \tag{15}$$

$$C_{AP} \doteq C_{AS} \tag{16}$$

$$R_{BP} \doteq 1/R_{BS}\omega^2C_{BS}^2 = 1/\eta_{BS}\omega C_{BS} \tag{17}$$

$$C_{BP} \doteq C_{BS} \tag{18}$$

$$C_{ABS} \doteq C_{ABP} \doteq C_{AP} + C_{BP} \doteq C_{AS} + C_{BS} \tag{19}$$

$$R_{ABS} \doteq 1/R_{ABP}\omega^2C_{ABP}^2 \doteq (\eta_{AS}\omega C_{AS} + \eta_{BS}\omega C_{BS})/\omega^2C_{ABS} \tag{20}$$

$$\eta_{ABS}C_{ABS} \doteq \eta_{AS}C_{AS} + \eta_{BS}C_{BS} \tag{21}$$

Equations (19) and (21) may be carried out for more than two condensers in parallel, and as long as the separate values of η are sufficiently low, the value of ηC for the parallel combination will be the sum of the values of ηC for the separate units, and the total capacitance

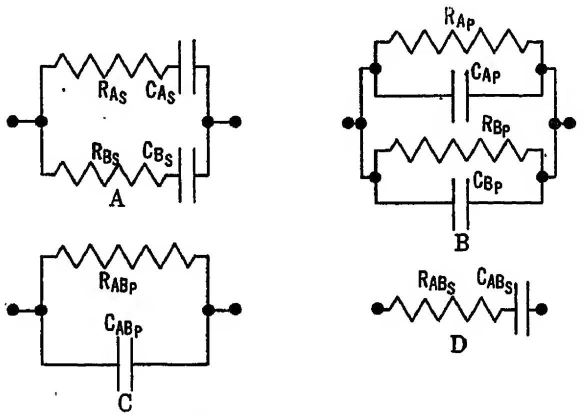

Fig. 6—Two Imperfect Condensers in Parallel

will be the sum of the separate capacitances, to a high degree of approximation.

A good variable condenser, such as must be used as a precision standard in this type of measurement, will have a minimum amount of stator supporting dielectric material placed where the electrostatic field is weak and where the movement of the rotor plates causes practically no variation in the flux distribution. This air condenser may then be considered as a variable perfect air condenser in parallel with a small "zero" capacitance containing the equivalent series resistance which represents the loss in the stator supporting dielectric material. Fig. 7A shows the equivalent circuit of the precision variable condenser and (B) and (C), the steps taken in finding its equivalent series resistance and capacitance as shown in (D).

By equations (12), (13), and (14)

$$C_{SS} \doteq C_{SP} \doteq C_{OP} + C \doteq C_{OS} + C \tag{22}$$

$$R_{SS} \doteq 1/R_{OP}\omega^2C_{SS}^2 \doteq R_{OS}\omega^2C_{OS}^2/\omega^2C_{SS}^2 \tag{23}$$

$$\eta_{SS}C_{SS} \doteq \eta_{OS}C_{OS} \tag{24}$$

This last equation indicates that the value of ηC of the precision condenser is approximately a constant regardless of the setting of the rotor plates. This is true to a very high degree of approximation.

The parallel substitution method of capacitance and power factor measurement is illustrated in Fig. 8. In using this method, the bridge is first balanced with the test specimen C_X connected in parallel with the pre-

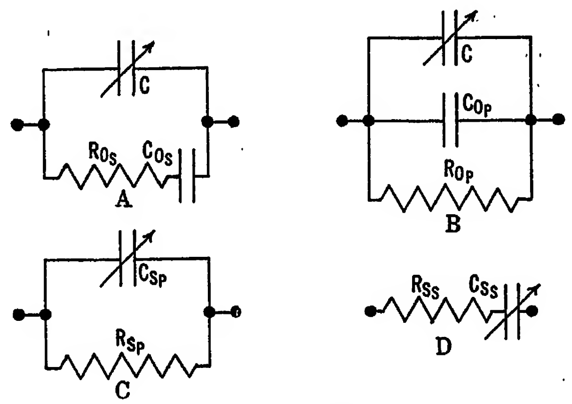

Fig. 7—Precision Variable Condenser

cision condenser C_5. If R_1 and R_2 are equal pure resistances, as is generally the case, the power ratio η_{3X} of the parallel circuit $3X$ must be equal at balance to the power ratio of the balancing arm, $(R_5 + R_4)\omega C_4$; also, the capacitance C_{3X} of the parallel circuit must be equal to C_4.

The value of ηC of the combination $3X$ is found by equation (21).

$$\eta_{3X}C_{3X} \doteq \eta_3C_3 + \eta_XC_X \tag{25}$$

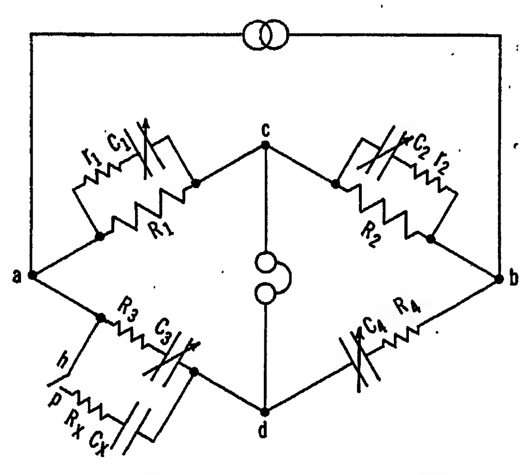

Fig. 8—Parallel Substitution Method

The lead h from the high tension side of the standard condenser, C_3, is then just removed from contact with C_X at p and the bridge rebalanced by adjustment of C_3 and R_5, C_4 being held constant. For this second balance, denoted by primes, the power ratios of the arms 3 and 4 must be equal and also $C_3' = C_4$.

Therefore, $\eta_3'C_3' \doteq (R_5' + R_4)\omega C_4^2$ (26)

In the first balance,

$$\eta_3 C_3 + \eta_X C_X \doteqdot (R_5 + R_4)\,\omega C_4^2 \tag{27}$$

By equation (24), ηC for the precision condenser is constant, so

$$\eta_3' C_3' \doteqdot \eta_3 C_3 \tag{28}$$

Subtracting (26) from (27), and using (28),

$$\eta_X C_X \doteqdot (R_5 - R_5')\,\omega C_4^2 \tag{29}$$

$$R_X \omega C_X^2 \doteqdot \Delta R_5 \omega C_4^2 \tag{30}$$

But since $C_4 \doteqdot C_3'$,

$$R_X \doteqdot \Delta R_5 (C_3'/C_X)^2 \tag{31}$$

$$C_X = \Delta C_3 \tag{32}$$

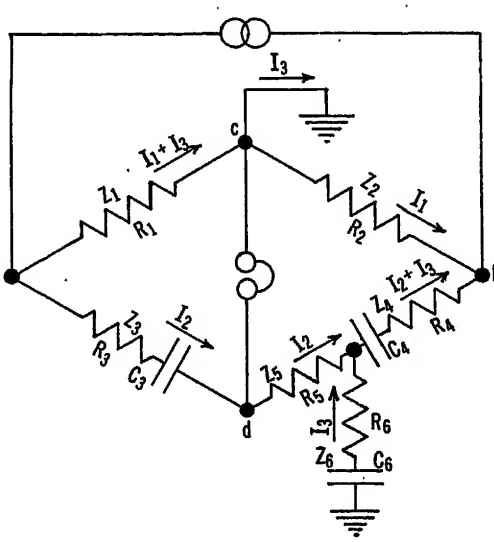

Fig. 9—Capacitance Bridge, Grounded at *c*

where ΔR_5 is the change in resistance of R_5 and ΔC_3 the change in capacitance of C_3 between the two balances, and C_3' is the value for the balance with lead h not in contact.

Appendix II

Derivations of Equations for the Bridge Circuits of Figs. 2 and 3 Considering Effect of Stray Capacitance C_6

Referring to Fig. 9 and writing the equations for balance,

$$(I_1 + I_3)\,Z_1 = I_2 Z_3 \tag{33}$$

$$I_1 Z_2 = I_2 Z_5 + (I_2 + I_3)\,Z_4 \tag{34}$$

$$I_2 Z_5 = I_3 Z_6 \tag{35}$$

Solving these equations simultaneously and eliminating the currents, the equation of balance is found to be

$$(Z_2/Z_1)\,Z_3 = [(Z_2 + Z_4)/(Z_6) + 1]\,Z_5 + Z_4 \tag{36}$$

If, as is usually the case, Z_1 is made equal to Z_2, the last equation becomes, after substitutions,

$$R_3 - j\,(1/\omega C_3)$$

$$= \left[\frac{R_2 + R_4 - j\,(1/\omega C_4)}{R_6 - j\,(1/\omega\,C_6)} + 1\right] R_5 + R_4 - j\,(1/\omega C_4)$$

$$= \left[\frac{\omega C_6\,\{(R_2 + R_4)\,\omega C_4 - j\,1\}}{\omega C_4\,\{R_6 \omega C_6 - j1\}} + 1\right] R_5 + R_4 - j\,(1/\omega C_4)$$

$$= \left[\frac{C_6\,(\eta_{24} - j\,1)}{C_4\,(\eta_6 - j\,1)} + 1\right] R_5 + R_4 - j\,(1/\omega C_4)$$

$$= \left[\frac{C_6\,(\eta_{24}\eta_6 + 1 + j\eta_{24} - j\eta_6)}{C_4\,(\eta_6^2 + 1)}\right] R_5 + R_4 - j\,(1/\omega C_4) \tag{37}$$

These second order η terms are negligible compared with unity, since they are of the order of magnitude of the squares of power ratios of air condensers. Therefore

$$R_3 - j\,(1/\omega C_3) \doteqdot [(C_6/C_4)\,(1 + j\eta_{24} - j\eta_6) + 1]\,R_5 + R_4 - j\,(1/\omega C_4) \tag{38}$$

Equating the real parts of (38),

$$R_3 \doteqdot [(C_6/C_4) + 1]\,R_5 + R_4 \tag{39}$$

This last equation shows that correct results can only be obtained for the resistance component of balance when the value of R_5 for each balance is multiplied by the factor $[1 + (C_6/C_4)]$.

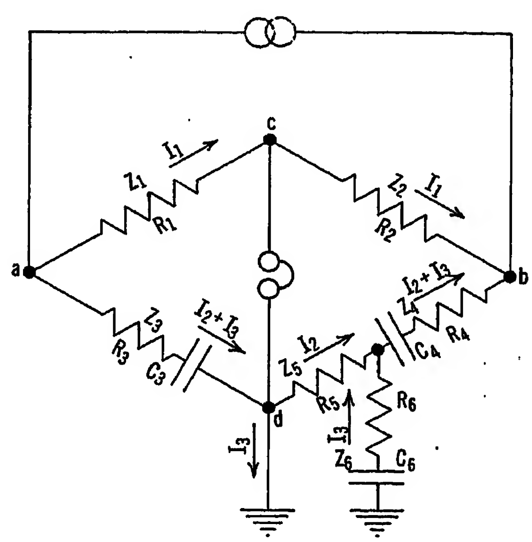

Fig. 10—Capacitance Bridge, Grounded at *d*

Equating the imaginary parts of (38),

$$-\,(1/\omega C_3) \doteqdot (C_6/C_4)\,(\eta_{24} - \eta_6)\,R_5 - (1/\omega C_4) \tag{40}$$

This can be written

$$1/C_3 \doteqdot [-\,\eta_{56}\,(\eta_{24} - \eta_6) + 1\,]/C_4 \tag{41}$$

Since the second order η terms are negligible compared with unity,

$$C_3 \doteqdot C_4 \tag{42}$$

This last equation shows that no error in the capacitance measurement is caused by the stray capacitance C_6.

Referring to Fig. 10, it is obvious that Z_5 is paralleled by Z_6. This parallel impedance is given by

$$Z_{56} = \frac{Z_5 Z_6}{Z_5 + Z_6} = \frac{R_5\,[R_6 - j\,(1/\omega C_6)]}{R_5 + R_6 - j(1/\omega C_6)} = \frac{R_5(\eta_6 - j\,1)}{\eta_{56} - j\,1}$$

$$= R_5\,[\eta_6\eta_{56} + 1 + j\,(\eta_6 - \eta_{56})]/(\eta_{56}^2 + 1)$$

$$\doteq R_5 + jR_5\,(-R_5\omega C_6) \tag{43}$$

Hence, $R_3 \doteq R_5 + R_4$ (44)

$$-j\,(1/\omega C_3) \doteq -jR_5^2\omega C_6 - j\,(1/\omega C_4) \tag{45}$$

$$C_4 \doteq C_3\,(1 + \eta^2) \doteq C_3 \tag{46}$$

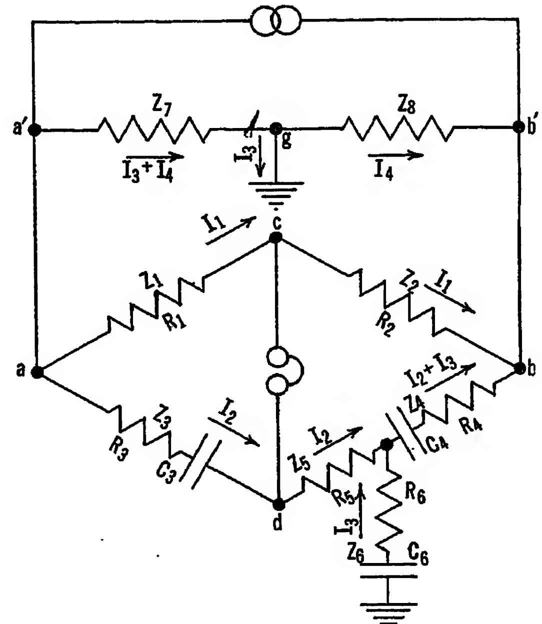

Fig. 11—Capacitance Bridge with Wagner-Ground Connection

There is therefore no appreciable correction due to the stray capacitance C_6 for this ground connection, at least not in the audio-frequency range.

Referring to Fig. 11 and writing the equations of balance,

$$I_1Z_1 = I_2Z_3 \tag{47}$$

$$I_1Z_2 = I_2Z_5 + (I_2 + I_3)\,Z_4 \tag{48}$$

$$I_2Z_5 = I_3Z_6 \tag{49}$$

Solving these equations simultaneously, eliminating the currents, the equation of balance is found to be

$$(Z_2/Z_1)\,Z_3 = [(Z_4/Z_6) + 1]\,Z_5 + Z_4 \tag{50}$$

Setting $Z_1 = Z_2$ and substituting,

$$R_3 - j\,(1/\omega C_3)$$

$$= \left[\frac{R_4 - j\,(1/\omega C_4)}{R_6 - j\,(1/\omega C_6)} + 1\right] R_5 + R_4 - j\,(1/\omega C_4) \tag{51}$$

Treating this last equation in the same manner as equation (37) gives the equation

$$R_3 - j\,(1/\omega C_3) \doteq [(C_6/C_4)\,(1 + j\eta_4 - j\eta_6) + 1]\,R_5 + R_4 - j\,(1/\omega C_4) \tag{52}$$

Equating the real parts of (52),

$$R_3 \doteq [(C_6/C_4) + 1]\,R_5 + R_4 \tag{53}$$

Equating the imaginary parts of (52),

$$-(1/\omega C_3) \doteq [(C_6/C_4)\,(\eta_4 - \eta_6)\,R_5] - (1/\omega C_4) \tag{54}$$

As before, this results in the relation

$$C_3 \doteq C_4 \tag{55}$$

Equations (53) and (55) show that the correction factor for R_5 still exists when a Wagner-ground connection is used although there is no error in the measured value of capacitance.

Appendix III

Derivation of Equations for Recommended Capacitance Bridge

Referring to Fig. 12 and assuming a balance with the lead h in contact at p, the impedance of arm ac is

$$Z_1 = \frac{R_1\,(r_1 - j1/\omega C_1)}{R_1 + r_1 - j1/\omega C_1} = \frac{R_1 r_1 \omega C_1 - jR_1}{(R_1 + r_1)\,\omega C_1 - j1}$$

$$= \frac{R_1 r_1 (R_1 + r_1)\,\omega^2 C_1^2 + R_1 + j[R_1 r_1 \omega C_1 - R_1 (R_1 + r_1)\,\omega C_1]}{(R_1 + r_1)^2 \omega^2 C_1^2 + 1}$$

$$\doteq \frac{R_1(\eta^2 + 1) - jR_1^2\omega C_1}{\eta^2 + 1} \doteq R_1 - jR_1^2\omega C_1 \doteq R_1(1 - j\eta_1) \tag{56}$$

since the η^2 terms are negligible compared with unity.

Similarly, the impedance of arm cb is

$$Z_2 \doteq R_2 - jR_2^2\omega C_2 \doteq R_2\,(1 - j\eta_2) \tag{57}$$

The condition of balance is that

$$Z_1/Z_2 = Z_{3X}/Z_4 \tag{58}$$

The second balance is obtained by just removing the lead h to C_X from contact at p, leaving C_4 at its original

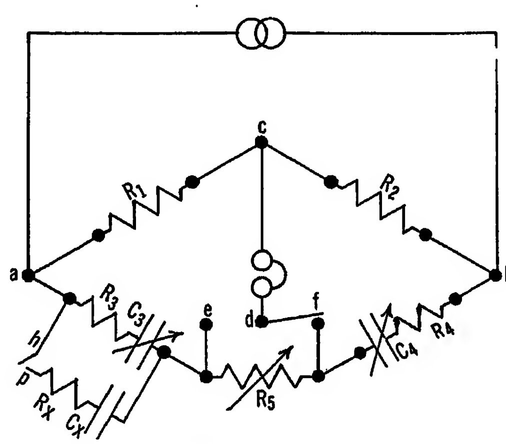

Fig. 12—Recommended Capacitance Bridge

setting, and rebalancing the bridge by variation of C_3 and either or both C_1 and C_2. Denoting this second set of values by primes, the condition of balance is

$$Z_1'/Z_2' = Z_3'/Z_4 \tag{59}$$

Dividing (58) by (59),

$$\frac{Z_1/Z_2}{Z_1'/Z_2'} = \frac{Z_{3X}}{Z_3'} \tag{60}$$

$$\frac{Z_1}{Z_2} \doteq \frac{R_1\,(1 - j\eta_1)}{R_2\,(1 - j\eta_2)} = \frac{R_1\,[1 + \eta_1\eta_2 + j\,(\eta_2 - \eta_1)]}{R_2\,(1 + \eta_2^2)}$$

$$\doteq \frac{R_1}{R_2}\,[1 + j\,(\eta_2 - \eta_1)] \tag{61}$$

since the η^2 terms are negligible compared with unity.

Similarly,

$$Z_1'/Z_2' = (R_1/R_2)\,[1 - j\,(\eta_2' - \eta_1')] \tag{62}$$

$$Z_{3X} = R_{3X} - j\,(1/\omega C_{3X}) = (\eta_{3X} - j1)/\omega C_{3X} \tag{63}$$

$$Z_3' = R_3' - j\,(1/\omega C_3') = (\eta_3' - j1)/\omega C_3' \tag{64}$$

Hence, (60) may be written

$$\frac{1 + j\,(\eta_2 - \eta_1)}{1 + j\,(\eta_2' - \eta_1')} \doteq \frac{C_3'\,(\eta_{3x} - j1)}{C_{3x}\,(\eta_3' - j1)} \tag{65}$$

Rationalizing,

$$\frac{1 + (\eta_2 - \eta_1)\,(\eta_2' - \eta_1') + j\,[(\eta_2 - \eta_1) - (\eta_2' - \eta_1')]}{1 + (\eta_2' - \eta_1')^2}$$

$$\doteq \frac{C_3'\,[\eta_{3x}\,\eta_3' + 1 + j\,(\eta_{3x} - \eta_3')]}{C_{3x}\,[(\eta_3')^2 + 1]} \tag{66}$$

Since the second order η terms are negligible compared with unity, (66) becomes

$$1 + j[(\eta_2 - \eta_1) - (\eta_2' - \eta_1')] \doteq (C_3'/C_x)[1 + j\,(\eta_{3x} - \eta_3')] \tag{67}$$

Equating the real parts of (67),

$$C_{3X} \doteq C_3' \tag{68}$$

By equation (19), Appendix I, $C_{3X} \doteq C_3 + C_X$, and hence

$$C_X \doteq C_3' - C_3 = \Delta\,C_3 \tag{69}$$

Equating the imaginary parts of (67),

$$(\eta_2 - \eta_1) - (\eta_2' - \eta_1') \doteq (C_3'/C_{3x})\,(\eta_{3x} - \eta_3') \tag{70}$$

By equation (21), Appendix I, $\eta_{3X}C_{3X} \doteq \eta_3 C_3 + \eta_X C_X$; by equation (24), Appendix I, $\eta_3 C_3 \doteq \eta_3' C_3'$; and by equation (67), $C_{3X} \doteq C_3'$. Substituting these relations in (70) gives the equations

$$C_3'\,[(\eta_2 - \eta_1) - (\eta_2' - \eta_1')] \doteq \eta_X C_X$$

$$\eta_X \doteq \omega\,(C_3'/C_X)\,[R_2\,(C_2 - C_2') - R_1\,(C_1 - C_1')] \tag{72}$$

An Automatic Oscillograph

BY C. M. HATHAWAY* and R. C. BUELL*
Associate, A.I.E.E. Associate, A.I.E.E.

INTRODUCTION

ALTHOUGH neither the oscillograph nor the art of oscillography is new, it has only been within the last few years that the oscillograph has been recognized as a thoroughly practical and necessary instrument for analyzing and solving many of the problems of operating engineers. This change in the status of the oscillograph from that of a laboratory device to an instrument of practical field utility has resulted from many recent improvements and simplifications in design, and from an increased demand for that type of instrument in modern engineering practise. Problems have arisen as a result of the new era of extensive interconnection of large power systems and of the high-speed operation of switches and circuit breakers that only an oscillograph can solve, and an oscillograph for such applications must have characteristics that are not found in those designed for more general uses. An oscillograph for such applications must, of course, be fully automatic because short circuits and faults are usually unanticipated; it should be able to take a considerable number of records successively whether the faults follow each other in rapid succession or are days or weeks apart, and it should start recording in as short a time as possible following the beginning of the initiating disturbance. With present-day oil circuit breakers having an operating time of eight cycles or less, and with relays which operate in one-quarter of that time, the oscillograph should certainly start its record in not more than one-half cycle. The automatic oscillograph described in this paper has been designed to meet the demand that has resulted for such an instrument by the advent of high-speed switching and relaying, and by the modern practise of clearing short circuits with extreme speed.

DESCRIPTION

The automatic oscillograph described herein will start recording with full speed within one-half cycle on a 60-cycle system after the current in the operating coil of its starting relay exceeds the critical tripping value. An oscillographic record is then taken at the rate of about 12 in. per second for a predetermined length of time that may be adjusted at will from 2 to 20 seconds, or until the disturbance is over if the fault outlasts this duration setting. The oscillograph will then stop recording, and will wait with no parts in motion for the next fault. The records are taken directly on sensitized paper 4¼ in. wide, and since a 200-ft. roll of this paper may be inserted in the oscillograph at one time, a great number of faults may be recorded in succession without intermediate attention of any kind. The roll of sensitized paper is placed in the right holder on top of the oscillograph, Fig. 1, and as it is exposed it is wound into the left holder. The left holder may be removed from the oscillograph at any time if it is desired to develop and examine the records it contains without waiting for the entire 200-ft. roll of paper to be exhausted.

The oscillograph contains six galvanometers, and each galvanometer may be used to measure either current or potential. The galvanometers are of the permanent magnet type. They employ the familiar bifilar type of moving element, and the records produced are truly oscillographic, showing wave shapes and phase relations as well as absolute magnitudes. The curves are traced on the sensitized record paper by small beams of light reflected from mirrors attached to the galvanometer moving elements. The light is obtained from a standard 6-volt, 32-cp. automobile headlight lamp that burns continuously.

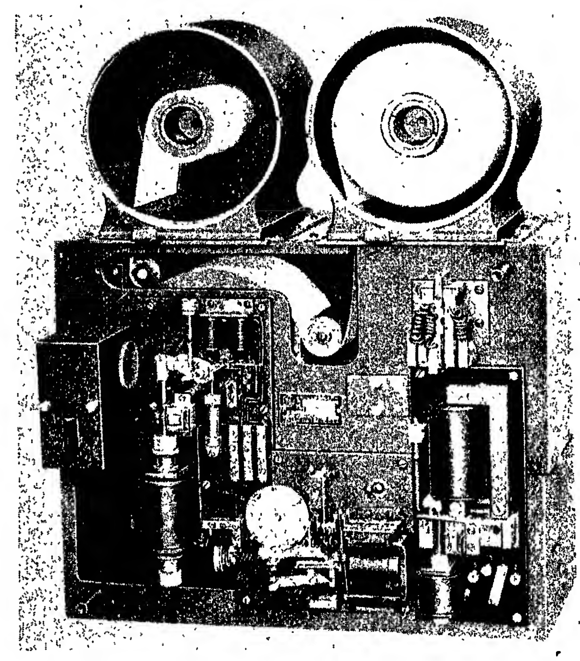

FIG. 1—AUTOMATIC OSCILLOGRAPH SHOWING RECORDING PAPER IN PLACE

Although no parts are in motion except during the time that the oscillograph is actually in operation, it will start its record within one-half cycle after the current in the starting relay exceeds the critical value. The method of obtaining this high starting speed will

*General Electric Company, Schenectady, N. Y.

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be made clear by an explanation of the schematic diagram of the optical system shown in Fig. 2. Referring to this figure, a spherical lens A focuses an image of the lamp filament B upon the front of the galvanometer E. The diverging beam from the galvanometer mirror passes through the cylindrical lens F and is reflected upward by the plane mirror G to the sensitized record-paper surface at K. An adjustable slit aperture D is placed between the source and the galvanometer, making it possible to vary the width

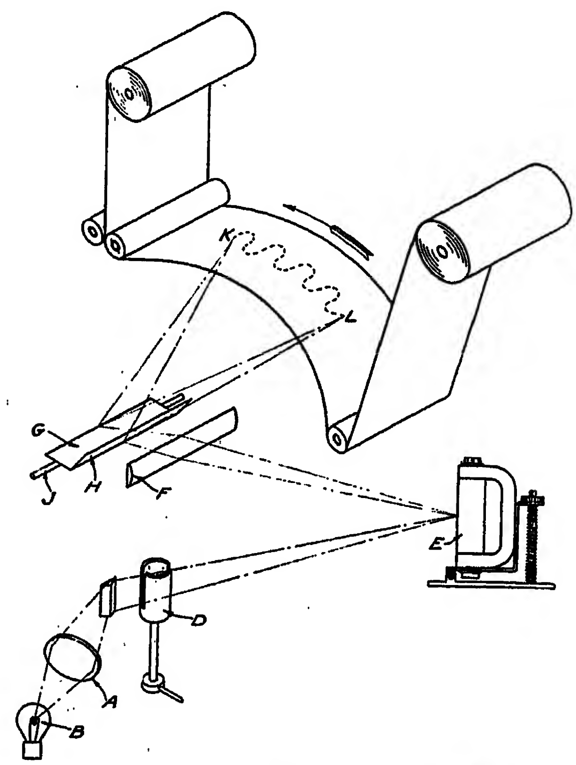


Fig. 2—Schematic Diagram of the Automatic Oscillograph Optical System

Only one galvanometer element is shown

of the light spot at K. When the starting relay is tripped, the mirror G rotates about the axis J and moves the spot of light from K to L along the sensitized surface, tracing the wave of the quantity actuating the galvanometer. While the spot of light is moving from K to L, the record paper is itself started in motion in the direction of the arrow, so that after the spot reaches the final position L the record is continued by the movement of the paper itself. This device renders it unnecessary to start an appreciable mass in motion in such a short time or to keep it in motion continually in anticipation of a disturbance to be recorded. Attached to the mirror G is a shutter vane H that intercepts the beam and prevents it from striking the record paper when the oscillograph is not in operation and the mirror G is in its extreme counter-clockwise position. A small rotation of G about its axis drops this shutter below the path of the light beam.

While the oscillograph is not recording, the mirror G, Fig. 2, is held in its extreme counter-clockwise position by the attraction of an electromagnet for an armature attached to the mirror shaft. The armature and the holding electromagnet are shown just below the record paper guides in Fig. 1. When the starting relay is tripped, this electromagnet is de-energized, the armature is released, and a spring rotates the mirror clockwise. The movement of the mirror is retarded by an oil dash-pot. Since the tension of the spring decreases as its elongation is decreased, the mirror moves with a retarded motion that combines with the accelerated motion of the record paper to produce an approximately uniform motion of the light beam relative to the record paper.

The starting relay is shown in the lower right-hand corner of the panel in Fig. 1. Its operating coil is intended to be connected directly in the secondary of a current transformer in the neutral connection of a generator or a transformer bank. Its armature is ordinarily held in the downward position by a small permanent magnet against the pull of a spring and the operating coil. Excessive current in the operating coil will pull the armature away from the permanent magnet, and since the attraction between the magnet and the armature is greatly diminished as soon as the contact between them is broken, the armature moves at a high speed when the current in the operating coil only slightly exceeds the tripping value. This device renders the starting speed of the oscillograph more nearly independent of the amount by which the current in the starting relay exceeds the tripping value.

The length of the record produced after each tripping of the starting relay is governed by the cam mechanism shown just to the left of the starting relay in Fig. 1.

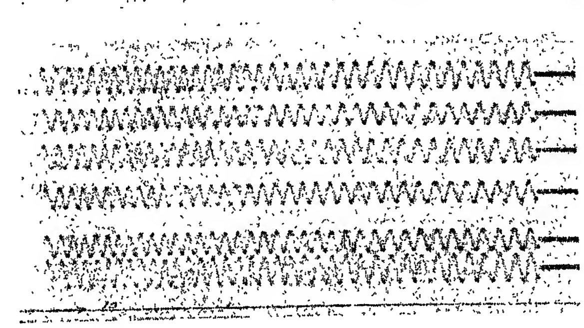


Fig. 3—Section Showing the Beginning of a Record Taken on the Automatic Oscillograph

This mechanism is driven by the motor that drives the record paper, and it may be adjusted to produce oscillograms of definite length of from two to twenty feet. It cannot, however, stop the oscillograph while the fault persists, so it is usually advisable to set it to produce the minimum record length of two feet. The oscillograph will then operate for only two seconds following a switching surge or a fault that is immediately cleared, but will automatically continue operation as long as the fault may persist. A counter

provided to record each operation so that the inspector may at any time determine the number of records the instrument has taken. A contact is also provided that may be used to close an alarm circuit during operation or to actuate a recording instrument or other type of time-recording device so that the exact time of each fault may be subsequently determined.

The power required for driving the record paper, for operating the lamp, and for energizing the holding magnet may be conveniently obtained from an ordinary automobile storage battery. The battery may be floated across a small charger that supplies continually enough current in excess of that required by the oscillograph while it is not in operation to keep the battery in good condition and always in readiness for service.

Application

This new automatic oscillograph may be applied to a power system to obtain a continuous check on the operation of the system equipment, or for special investigation of some transient phenomena which occurs during a system disturbance. The following

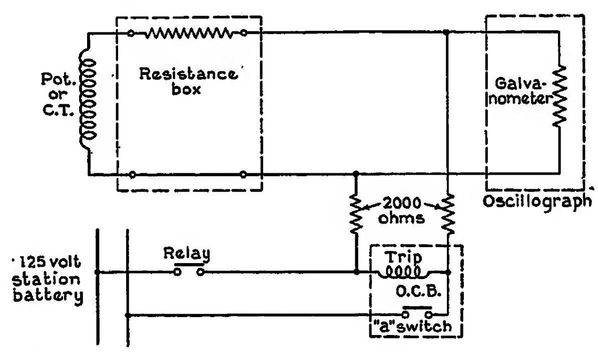


Fig. 4—Circuit for Indicating Relay and Oil Circuit Breaker Operation

are some of the most common factors, which are of considerable interest during any system disturbance.

1. The three-phase voltages on the station bus.
2. Sequence and time of operation of relays and oil circuit breakers.
3. Phase and neutral currents.
4. Kilowatts of generators or tie-lines.
5. Action of voltage regulators.
6. Generator speed and governor operation.
7. Pressure in penstocks, oil circuit breakers, etc.

An over-current relay is furnished to start the oscillograph when a disturbance occurs. This is usually connected to a current transformer in the grounded neutral of a power transformer bank. By connecting such current transformers in parallel the oscillograph may be started by any one of several neutral grounding connections.

In some locations it is impossible to obtain neutral current to start the oscillograph, and undervoltage or overvoltage is the desired indication for the oscillograph to come into operation. Additional relays which will operate under these conditions are available and can be arranged to operate in parallel with the overcurrent relay.

When the oscillograph is used as an aid in the analysis of system operation, it is often installed at a station which has a number of important transmission lines radiating to other sections of the system. The usefulness of the oscillograph can be greatly increased in such a location by the use of circuits similar to that shown in Fig. 4. Such a circuit will not affect the continuously recorded wave and will also show which oil circuit breaker operated, and the length of time for its relay and mechanism to function. With this circuit the zero line of the continuously recorded wave will be off-set when the relay contacts close and will return to normal when the oil circuit breaker opens.

During the past summer, one of these automatic oscillographs was installed at a main substation of a large operating company. More than 200 records of disturbances were obtained. Some records show conditions of instability, double-circuit faults with attendant slow relaying have been common, and two interesting records show the current decay as the arc of a short circuit to a steel tower blew away from the insulator string and finally went out entirely. Several cases of incorrect equipment operation have been found which otherwise would have been overlooked.

Conclusions

A new automatic oscillograph has been described which has been designed primarily for the recording of chance and unanticipated disturbances in power systems and in electrical machinery. Chief among the characteristics which render it useful for the applications for which it was designed are the following:

1. It can be automatically started by the disturbance which it is intended to record, and it automatically continues in operation until that disturbance is over.
2. Although no parts are in motion while it is not actually recording, it starts recording at full speed within one-half cycle of a 60-cycle system after the current in the starting relay exceeds the tripping value, regardless of the amount by which it may exceed this value.
3. Since a 200-ft. roll of record paper may be inserted at one time, it is capable of taking a large number of records in succession without intermediate attention. The records obtained may be removed at any time without waiting for the entire 200-ft. roll to be exhausted.
4. The records obtained are truly oscillographic, and the speed is great enough to show wave shapes and phase relations as well as absolute magnitudes.
5. The records are taken directly on sensitized paper that is cheaper than film and that produces black lines on a white background immediately after development.
6. The automatic oscillograph may be used to obtain a continuous check on relay operation and oil circuit breaker performance, as well as records of currents, voltages, power, governor operation, penstock pressure, etc., during disturbances.

Discussion

Wm. G. Walker: During the summer of 1930 the development model of the automatic oscillograph described today was installed at the Plymouth Meeting Substation of the Philadelphia Electric Company on the Pennsylvania-New Jersey 220-kv. interconnection lines in order to obtain field experience in the application of such an instrument for recording transient disturbances.

The results of this preliminary installation provided both the manufacturer and the operating company with valuable data showing what might be expected from the application of such an instrument to this purpose. Several of the suggestions advanced by the men responsible for maintaining the instrument during this experimental period have been incorporated in the commercial model.

A commercial model of the device was installed, in conjunction with other oscillographs, at Plymouth Meeting Substation August 6, 1931, and remained in service until temporarily removed for use elsewhere on January 13, 1932. A record of the performance during the 160 days it was installed is of interest.

During this time there were 63 operations from all causes, including testing, as contrasted with the experience cited in the paper covering another installation. Of the 63 operations 21 were the result of system disturbances initiating the instrument. There were 57 correct records obtained. The failures to obtain correct records were due to the following causes:

Three were lost as the result of a burnt out lamp within an interval of 40 minutes.

Two were lost as the result of improper loading within an interval of 4 minutes.

One was lost due to the oscillograph being blocked in the inoperative position for a switching operation.

It will be seen from the above detailed causes that none of the records was lost through failure of the instrument to function.

At the time the records were lost due to a burnt out lamp, data were being accumulated to determine the actual life of these lamps. Sufficient information had already been obtained to indicate that the lamp in question should have been replaced.

The two records which were chargeable to improper loading were directly due to improper maintenance. The case in which the record was lost due to the oscillograph being blocked, was the result of operating instructions issued to reduce the cost of maintenance on other oscillographs on the system, and the unnecessary consumption of film resulting from their initiating on unimportant switching transients.

The earliest experience with the device indicated that the standard Mazda 32-cp. automobile headlight lamp No. 1133 had an average lamp-life of 12.8 days at 6.6 volts battery. Just prior to the temporary removal of the commercial instrument, a new lamp for this purpose was being investigated. At the time the installation was removed the new lamp was still burning satisfactorily after 16 days service. The performance of this new lamp indicates that the lamp-life question has probably been satisfactorily answered although the data are not conclusive.

No particular difficulty was encountered in stabilizing the charge on the supply storage battery to give the desired voltage at the oscillograph terminals. This was accomplished by inserting adjustable resistance in the primary of the tungar charger, observing the gain or loss in battery voltage with the oscillograph connected, and making the necessary adjustments until stability was obtained.

It is our opinion that the ability of this instrument to take 100 consecutive 2-ft. records, without attention, is a considerable advantage where an instrument of this type must be installed at locations which are more or less remote from the headquarters of a specialized maintenance group. Although operating men can be trained to service oscillographs satisfactorily, still at the same time it must be remembered that at times of major system disturbance their primary concern is restoration of normal service. With the instrument under discussion the only duty which develops upon the operator is to log the operation and its corresponding number on the operation counter.

Our experience indicates that the frequency of inspection of this instrument depends entirely upon the life of the lamp and this may result in a two or three week period, depending upon the results obtained with the new lamp. These lamps are made to very close specifications and may be replaced by the regular operating force without disturbing the light focus enough to interfere with the operation of the instrument. There is apparently an adequate supply of light to obtain satisfactory records with a lower voltage than 6.6 volts applied to the oscillograph but it is our opinion that the quality of the records should not be jeopardized in this way.

The instrument is interchangeable for either table or panel mounting. Standard switchboard terminal studs are used when it is panel mounted, thus permitting all wiring to be installed in accordance with local standards.

The Photoelectric Recorder

BY C. W. LA PIERRE[1]

Associate, A.I.E.E.

INTRODUCTION

THE usual direct-acting recorders are the heavier and higher torque counterparts of corresponding indicating instruments. Although such recorders have some highly desirable characteristics, such as a continuous record and a rapid response, they cannot be made to approach indicating instruments in sensitivity.

The photoelectric recorder combines all the advantages of direct-acting recorders with those of the most

FIG. 1—PHOTOELECTRIC RECORDER WITH PORTABLE FIXTURES

sensitive indicating instruments. This is accomplished by providing a separately excited recording element to do the actual work of making the record. A sensitive indicating instrument controls the position of the recording element so that the record obtained represents the readings of this basic instrument. The loss in the sensitive basic instrument is the only power required from the measured circuit.

The link between basic and recording elements consists of a combined optical system and photoelectric circuit. The basic element itself rotates a galvanometer mirror through an angle corresponding to its reading, and can be even more sensitive than the usual indicating instruments with pointers. On the other hand, the recording element may readily possess as much torque and be as heavy and sturdy as desired without affecting the basic element or measured circuit in any way.

As a result, the photoelectric recorder possesses all of the desirable characteristics of direct-acting recorders, and at the same time is capable of a sensitivity and a rapidity of response equal to the highest sensitivity indicating instruments. In general, anything which can be indicated can now be continuously recorded by means of the photoelectric recorder.

DESCRIPTION

An external view of one form of the photoelectric recorder is shown in Fig. 1. The instrument is completely self-contained requiring only an auxiliary source of 115 volts, 60 cycles. It is available for either portable or switchboard use.

The internal parts of the photoelectric recorder may be grouped into five units: namely, the basic indicating instrument or galvanometer, optical system, recording element, chart carriage, and power unit. The relative location of the various units is shown in Fig. 2.

The Basic Instrument is the only measuring device within the recorder. Ample space is available for in-

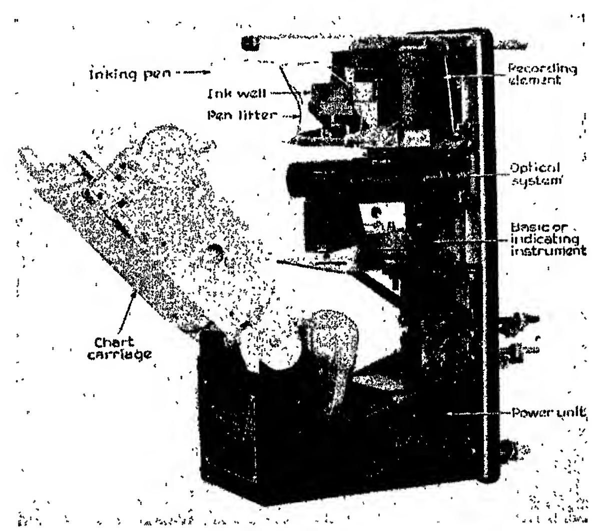


FIG. 2—INTERIOR OF THE PHOTOELECTRIC RECORDER

cluding almost any type of normal size instrument element. For use in the recorder their pointers are removed and replaced by a small galvanometer mirror usually mounted on the axis of rotation, just above the basic instrument proper. A typical mirror and mounting for this purpose weighs approximately 0.07 gram.

The Optical System includes mirrors on the basic and recording elements and the fixed reflectors shown in Fig. 3. A schematic diagram of the complete system is

1. General Engineering Laboratory, General Electric Co., Schenectady.

Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 25-29, 1932.

illustrated by Fig. 4A. Fig. 3 also shows side reflectors which are for the purpose of directing the light into the photoelectric tubes when it fails to strike the dividing reflector.

In general, the optical system comprises a group of reflectors, so arranged that whenever an angular displacement between the recording and basic elements occurs, there will be a shift in the light distribution between the photoelectric tubes, of the proper direction to react on the recording element and reduce the displacement to zero. Thus the optical system always acts to maintain the recording and basic elements in the same angular position.

The manner in which this is accomplished may be determined by inspection of Fig. 4A. The important reflectors in this group are: the basic element mirror A, the curved reflector B, the recording element mirror C, and finally the dividing reflector D which splits the light and reflects each portion into its photoelectric tube. The recording and basic elements are usually located on the same axis, or very nearly so, although this is not necessary for successful operation of the instrument. The lamp and condensing lens converge a source of light

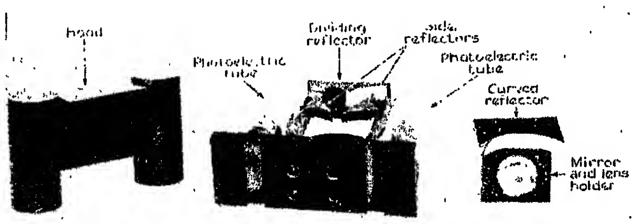


FIG. 3—FIXED REFLECTORS OF THE OPTICAL SYSTEM

upon the basic element mirror A, from which it is reflected to the curved mirror B. The point at which the light strikes the mirror B will depend upon the angular position, or in other words, "the reading" of the basic element. Regardless of where it strikes B, however, it is reflected to C. The angle at which the light leaves C will depend upon the angle at which it arrived from B and also upon the position of the recording element. When C and A are parallel, however, the light will leave C and split evenly upon the dividing edge D. This holds regardless of the actual position of A and C; the only requirement is that they must be parallel. If they are not, the light will strike to one side of the edge of D; more of it will pass into one photoelectric tube or the other and cause the recording element to turn until they are parallel. The relation between the various angles of incidence and reflection are shown in Fig. 4B. Here, by slightly displacing the mirrors from their true positions, the different paths of light can be readily traced.

The light does not, of course, traverse the optical system as a parallel ray and the optical constants of the system are of major importance. These factors are considered more in detail in the appendix.

The Photoelectric Circuit which supplies the actual energy used by the recording element in making the record is shown in Fig. 5. The output of a secondary winding on the auxiliary supply transformer is rectified and applied to the field coils of the recording element. A capacitor in parallel with the field coils provides

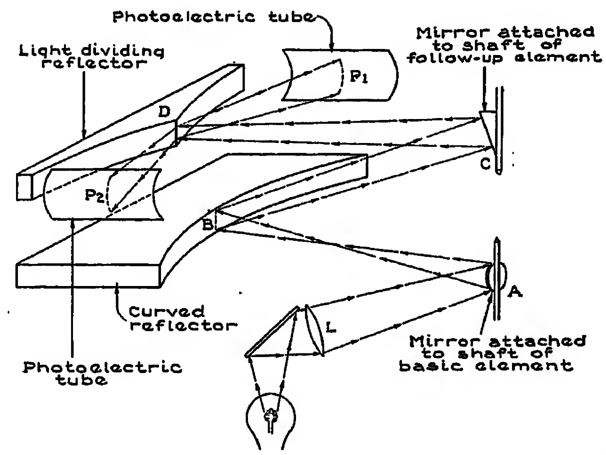


FIG. 4A—SCHEMATIC DIAGRAM OF THE OPTICAL SYSTEM

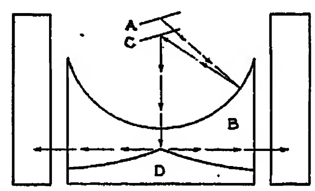


FIG. 4B—VARIABLE ANGLES OF REFLECTION OF THE OPTICAL SYSTEM

additional filtering so that the pulsations in the resulting direct voltage are considerably reduced. The voltage so obtained supplies the pliotron plate and the photoelectric tube circuits. Other windings on the auxiliary supply transformer provide voltages for the lamp, rectifier, and pliotron filaments.

Of greatest importance is that part of the circuit beyond the field coils of the recording element. A portion

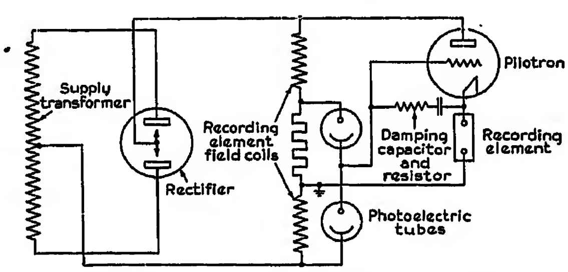


FIG. 5—SCHEMATIC DIAGRAM OF THE PHOTOELECTRIC CIRCUIT

of the direct voltage across the field coils is applied to the three element pliotron tube. The plate current of this tube passes through the recording element armature connected in the filament side of the circuit to permit grounding one armature lead. Another portion of the voltage across the field coils is applied to the two

vacuum type photoelectric tubes in series. Their common junction is connected to the grid of the pliotron. This circuit is capable of very high sensitivity to changes in the distribution of illumination between the two tubes. The slightest unbalance of light in a given direction between the tubes will throw the grid voltage to one extreme. A slight unbalance in the opposite direction will throw the grid voltage to the opposite extreme. These extreme grid voltage swings occur far too fast under normal conditions to make the circuit

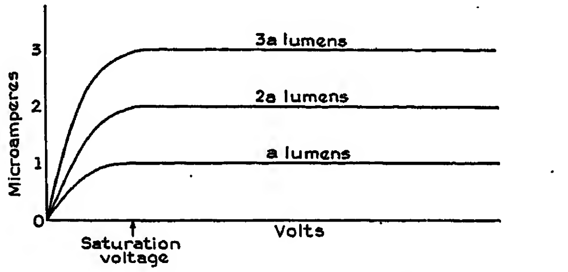


FIG. 6—CHARACTERISTIC CURVES FOR VACUUM TYPE PHOTOELECTRIC TUBES

useful for purposes of recording. The high sensitivity may be retained with all its advantages, however, and still have the circuit as slow in operation as may be desired. This is accomplished by inserting between the grid and filament a capacitor and resistor in series. It is now necessary to alter the charge upon the capacitor before the grid voltage can change, and the time lag of this procedure may be adjusted to any degree by changing the value of the capacitance. Without this damping circuit there would be violent hunting between the recording element and the electric circuit, whereas with the damping circuit all tendency to hunt or overshoot can be completely eliminated.

Besides providing a circuit highly sensitive to changes in light distribution, the vacuum type photoelectric tubes contribute materially toward the high precision obtainable in the transfer from the basic to the recording element. This property can be readily explained on the basis of the characteristic curves of Fig. 6.

As applied to the present case the tubes are always operated at voltages beyond the saturation value indicated by the arrow on the curves. Under this condition the circuit of Fig. 5 has the same light distribution between the two photoelectric tubes regardless of the particular plate current at which the pliotron may be operating. There is, of course, a momentary change every time the basic instrument shifts, but when the recording element takes up its new position the light distribution returns to its former value. This characteristic arises from the fact that above saturation the photoelectric tube current is independent of voltage. In the strictest sense, the tubes are electron valves controlled solely by light. In Fig. 5 it can be shown that the position the optical system always seeks is the condition of equal photoelectric tube currents. If the currents are not equal the grid voltage must be changing as the difference current can only flow into the grid capacitance. Since the photoelectric tube currents are sensitive only to light, it follows that the light distribution must always be the same in order that the tube currents may be equal.

The Recording Element: The particular form assumed by the recording element is not of very great technical importance in the photoelectric recorder whereas in direct-acting types the recording element must be a highly reliable and accurate device. In the present instrument it exists merely for the purpose of actuating the recording pen. Within wide limits its characteristics do not enter at all into the accuracy of the instrument, for its position is controlled by the basic element.

The recording element contained in the instrument of Fig. 2 is illustrated in detail in Fig. 7. This differs from the d'Arsonval type in having an electromagnet instead of a permanent magnet field. The armature consists of a coil moving in the gap formed by the pole pieces and core. The armature current is obtained from the pliotron tube and is under the control of the photoelectric tubes. The field winding derives its current from the output of a rectifier on the secondary side of an auxiliary supply transformer. This transformer is contained in the power unit and also supplies all filament and other necessary voltages. The electromagnet field serves an additional function as the voltage divider and filter inductance for the direct current supplied to the pliotron and photoelectric tubes.

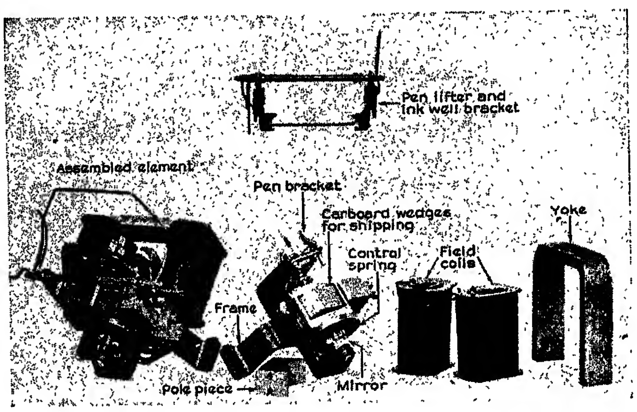


FIG. 7—THE RECORDING ELEMENT

The inking system, comprising a syphon pen and a fixed ink reservoir, and the chart carriage, are of conventional design.

SENSITIVITY AND RAPIDITY OF RESPONSE

The sensitivity of the recorder is dependent only upon the sensitivity of the basic element. Rapidity of response is usually governed by the period of the basic element, although in some isolated cases the period of the recording element may be the limiting factor. Recorders can be constructed utilizing as a basic element

almost any indicating instrument or galvanometer that is capable of rotating a mirror as a means of indicating its readings. For recorders that are expected to be carried about and used like any switchboard or portable instrument, the use of extremely sensitive galvanometers with long suspensions is impracticable. However, extraordinarily high sensitivities can be obtained with the more sturdy pivoted instruments. The following discussion gives some idea of what can be readily accomplished.

For d-c. measurements the basic element is usually the same as is found in miniature indicating elements, except that a galvanometer mirror is substituted for the pointer. Such miniature elements are available to provide recorders of as low as 75 microamperes full scale and having a resistance of 350 ohms. Higher currents and other resistance values are also available. A low watt consumption element may be used having a full scale current requirement of 300 microamperes and a resistance of only 10 ohms. A recorder containing this instrument would require less than 1 microwatt from the measured circuit at full scale deflection. With larger elements of slightly more expensive construction, current sensitivities of 20 microamperes full scale can be provided with a watt consumption at that current of approximately 0.3 microwatts.

The figures just given illustrate very forcibly the extremes to which sensitivity has been carried in the photoelectric recorder. Such instruments are not at all delicate. In fact, because of the small weight of their moving systems, they are much more free from difficulties due to rough handling of the recorder than are heavier and less sensitive elements.

Other elements are, of course, available for recording other quantities. For instance, high sensitivity frequency recorders can be constructed with a scale range of 1 cycle at 60 cycles; high sensitivity voltage recording with a scale range of as low as 4 volts on a 115 volt circuit; pressure recorders with full scale pressures down to approximately 1 or 2 inches of water; or, in general, anything for which there is some sort of an indicating instrument, can be continuously recorded with a photoelectric recorder.

The rapidity with which the recorder responds to fluctuations in the measured quantity is of the same order as the response of the basic element. In most cases the instrument responds to a change from zero to full scale within one second, and the usual fluctuations require a much shorter time.

ACCURACY

Many amplifying systems have been devised for using electron tubes in connection with the measurement, recording and control of various quantities. Such amplifying systems are usually effected by variations in the characteristics of the lamps and electron tubes used, and are also subject to variations in the supply voltage. The optical system and photoelectric circuit described above is self-compensating for all normal changes in these variables.

Variation in the Auxiliary Supply Voltage is transmitted to all parts of the photoelectric circuit. However, within wide limits, such variations do not affect the accuracy of the recorder. When the voltage does change, the recording element current will also change momentarily. The resulting shift in the recording element will cause the photo tubes to establish a new grid potential and restore the proper plate current in spite of the changed supply voltage. As these changes occur very rapidly and with a very small movement of the recording element, there is ordinarily no discernible effect upon the record.

Changes in Pliotron Characteristics such as occur due to variation of filament emission, etc., are automatically compensated for by the circuit in the same manner as are voltage fluctuations. No change whatever would be expected in the record due to variations between individual tubes as long as they are of the proper type. In fact this circuit has been constructed with sufficient margin to permit using tubes of widely different characteristics including different filament and plate voltage ratings as well as different values of amplification constant, μ, without any appreciable effect upon the accuracy of the result.

Changes in Lamp Illumination such as occur due to normal variations in supply voltage, deterioration of the filament and blackening of the bulb do not ordinarily produce any effect on the recorder during the life of the lamp. In extreme cases of progressive loss of illumination, the operation of the recorder may be slowed up appreciably without, however, affecting its accuracy.

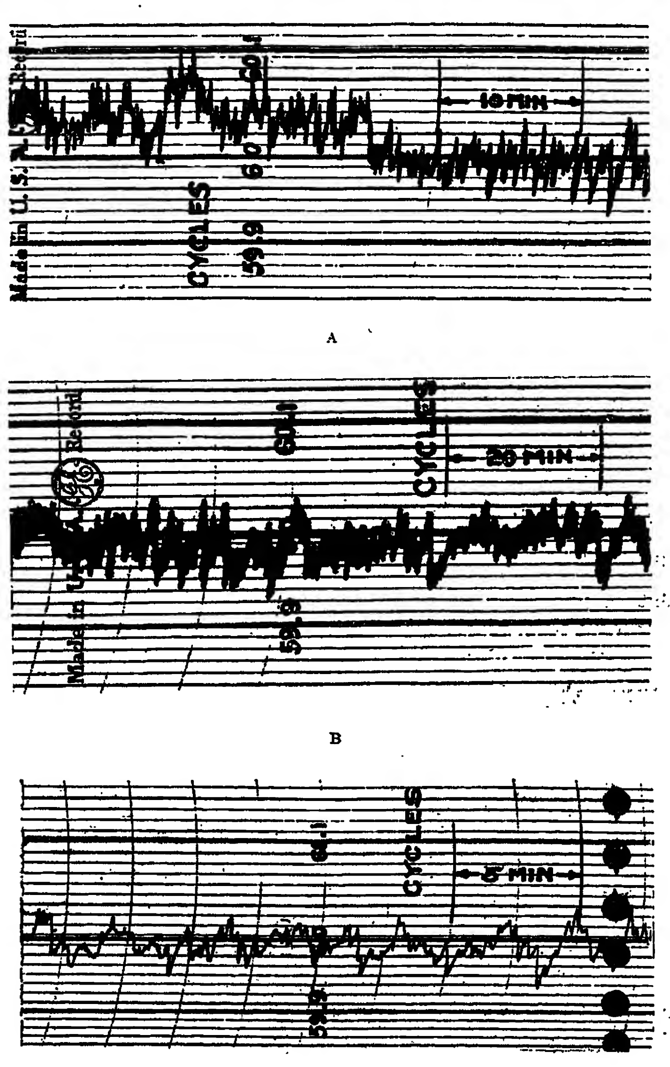
The Reflectors merely direct the illumination along the desired paths, and variations in their reflecting power, such as those due to accumulations of dust, have the same effect as variations in lamp intensity. Here again serious errors are extremely unlikely, for any trouble is readily detected in the noticeable slowing down of the operation of the instrument long before it develops any appreciable errors.

It is interesting to note, however, that ordinary dust accumulations on the reflectors produce an inappreciable effect on their reflecting power. No matter how dusty the reflectors may appear to the eye, an inspection of the surface through a microscope will show that the particles are widely separated.

Variations in Photoelectric Tube Sensitivity may be added as the final possible source of error of any magnitude. Here again, through proper design of the optical system, the effects of changes in photoelectric tube sensitivity have been reduced to a secondary and negligible order of magnitude. The use of vacuum type tubes is also of considerable advantage as they are much more stable than gas-filled types.

The action of the recorder in respect to these factors may be explained by reference to Figs. 4A and 5. The condition the recording element always seeks is that

occurring when the two photoelectric tube currents are equal. If the tubes are not of equal sensitivity, the equal currents can be obtained only by throwing more light on the less sensitive tube. This is actually what happens when tubes having different sensitivities are used. After they are installed and the instrument is set to zero, it will work satisfactorily, and unless the difference in sensitivity is quite large, no one would be able to detect it from the operation of the instrument. In case the difference in sensitivities is large, in the order



A

B

C

FIG. 8—HIGH SENSITIVITY FREQUENCY RECORDS

of two or more to one, for instance, it would be noticed that the recorder followed more rapidly going one way on the scale than the other, and the trouble is readily remedied by replacing the less sensitive tube.

Tests show that after photoelectric tubes have been in service a while, they tend to become quite stable and will maintain their sensitivities fairly constant over long periods. There is still some variation, however, and it is desirable to show just what effect this has upon the recorder.

Assuming for the present that the two photo tubes of equal sensitivity are installed, the light CD in Fig. 4A will split evenly at D into the two tubes for all scale readings. If the sensitivity of one photo tube decreases with respect to the other by 50 per cent (a very unlikely amount) it would mean that the less sensitive tube would require twice the illumination of the other. This would be obtained by a shift in the light ray CD. The amount of shift would depend upon the effective width of the ray at D. In a specific case, the effective width of the ray is 0.12 inch. Thus for photoelectric tubes of equal sensitivity the split rays would each be 0.06 inch wide at D. If one photoelectric tube is to receive twice the illumination of the other, due to a change in relative sensitivity, the two rays would be 0.08 inch and 0.04 inch wide. The actual displacement from the former position is 20 mils. This results in an angular displacement of less than 40 minutes for a length of CD equal to 1.75 inches. Since the recording element need rotate through only 20 minutes to produce a 40-minute movement in the ray (the reflection at C doubles the angle), the actual error in the position of the recording element is quite small, amounting to only 0.6 per cent of full scale deflection. It is not expected that the vacuum type photo tubes used in the recorder will change relative to one another by any such amount as 50 per cent, in fact, the variations are more nearly 5 per cent. Consequently, the error due to this cause is limited to the order of one-tenth of one per cent at most, and this would occur only over a considerable period of time.

The Other Possible Sources of Error include pliotron grid currents, photo tube dark currents, and leakage currents in the grid circuit. All of these tend to affect the results in the same way as a change in photo tube sensitivity. There is no difficulty, however, in reducing the magnitude of all stray currents to from one-tenth to one-twentieth of the actual control current. When of this order their effect is entirely negligible.

It is believed that in any new instrument of this kind, the possible sources of error should be investigated very carefully. It is for this reason the preceding discussion has been carried out in considerable detail. The mere mentioning of a possible source of error should not in any way be interpreted to mean that it is an important one. In fact they have all been mentioned and discussed only for the purpose of showing how very small are their possible effects.

OPERATION

Several of the photoelectric recorders both in experimental and commercial forms have been under observation under actual operating conditions for some time. The results they have produced are in many cases such as could not be obtained by any other commercial instrument with which the author is familiar.

Figs. 8A, B, and C show frequency records at various chart speeds, made on a well-regulated system. Records such as these show very clearly the variations between

the control limits of the regulating devices. They are especially useful in studying system frequency disturbances.

Fig. 9 illustrates sensitive voltage records taken on a constant voltage supply for laboratory use. Recorders of this sensitivity are almost a necessity in running life tests on the filaments of lamps and tubes of various kinds, and in other cases where small variations in voltage produce large variations in the data to be obtained.

Fig. 10 illustrates records of smoke intensity taken in the stack of a steam generating furnace. In this case the recorder was used in connection with a photoelectric smoke detector. Such applications emphasize the usefulness of the photoelectric recorder in connection with other electron tube apparatus. The use of ordinary recorders requires at least one more stage of amplification and the record is subjected to the additional errors of that stage. In photoelectric tube work the photoelectric recorder can often be constructed to record the photo tube currents directly so that the only errors in the record are those of the tube itself. Additional discrepancies due to amplifying equipment are completely eliminated.

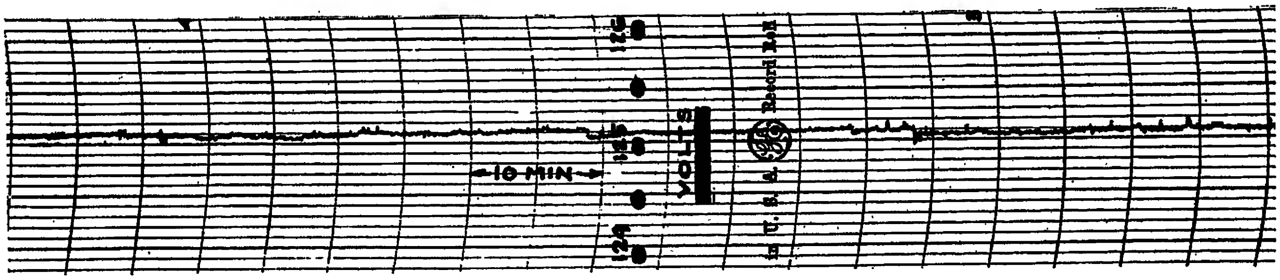


FIG. 9—HIGH SENSITIVITY VOLTAGE RECORD

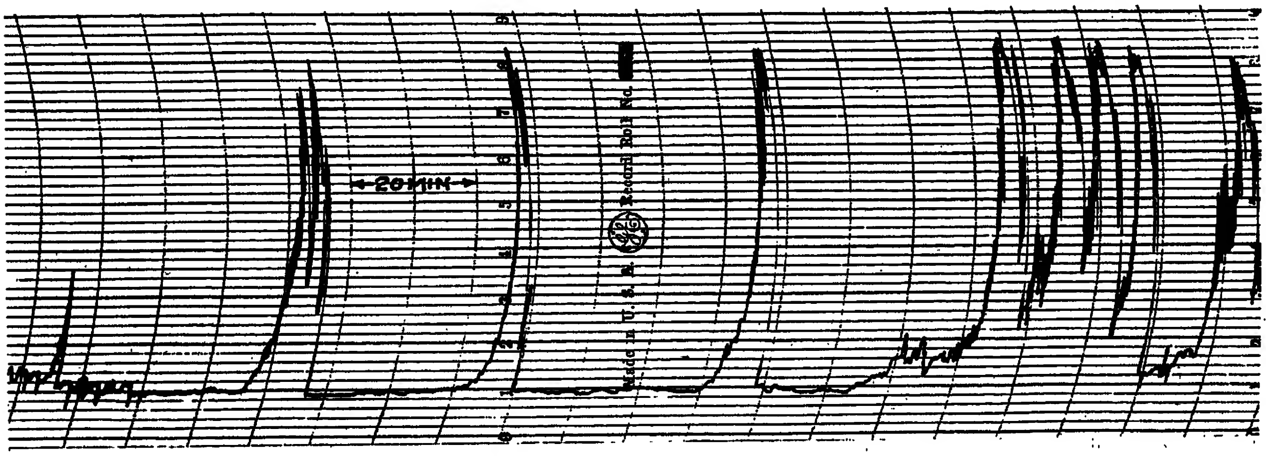


FIG. 10—SMOKE INTENSITY

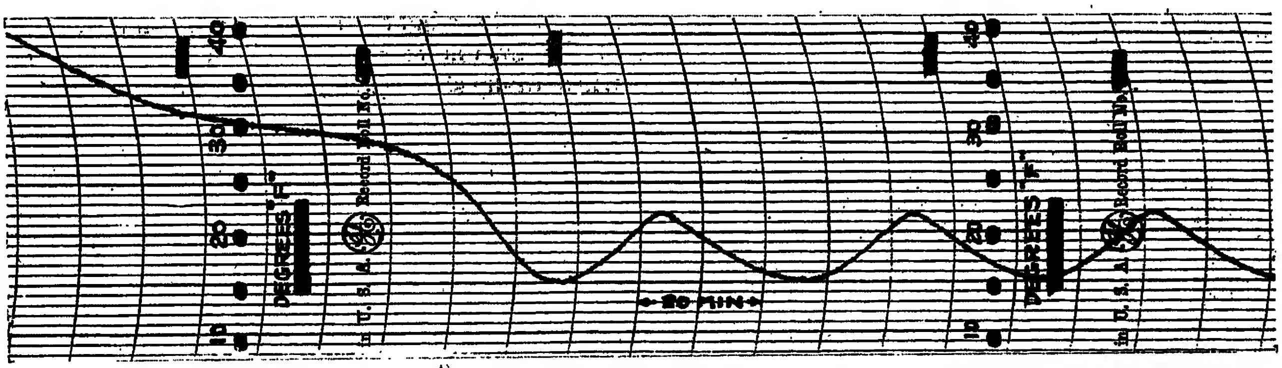


FIG. 11—REFRIGERATOR EVAPORATOR TEMPERATURES DURING TEST

Fig. 11 illustrates records taken of variations in the temperature of a refrigerator evaporator under test.

In connection with an electric gage, continuous records have been taken of paper thickness as it passes from one roll to another. Each small division on the

fifty division chart represented a variation in thickness of two one-hundred thousandths of an inch. Other gaging records have been obtained showing the dimensions and distortion of materials under stress.

Still other applications include electrolysis survey records, turbo-generator vibration recording, high sensitivity power recording, small draft pressures and so on.

The Maintenance necessary in the operation of the instrument has been reduced to a very low minimum. Aside from chart replacement and refilling the ink well, there is nothing much else to be done. Since the lamp and tube filaments operate at less than normal voltage, their replacement is a very infrequent occurrence. The estimated lamp life is from 3 to 5 months for continuous operation, and the other filaments are designed to last well over a year under the same conditions. As the phototubes have no filaments to burn out, their life is indeterminate, but they should last at least as long as any of the other tubes.

Lamp replacement may require a slight adjustment in order to get a good focus of the filament image on the dividing edge of the reflector *D*, Fig. 4A. This adjustment is easily made and is only necessary when the position of the new filament differs from the previous one. The replacement of the other tubes should require no adjustment whatever. As in the case of most instruments, it is good practise to reset the pointer on zero after making any adjustments.

Conclusions

In making possible the precise control of unlimited power by the most sensitive instrument elements, it is obvious that many instrument problems arising from insufficient torque have been solved. Especially is this true in regard to the two major problems of recording; sensitivity and rapidity of response. Of greater fundamental importance, perhaps, is the combination of ordinary lamps and electron tubes, with all their well-known characteristics, into a conveniently operated instrument capable of the highest precision.

Appendix

The Optical System

In the design of the optical system two factors are of dominant importance. First the amount of illumination striking the photo tubes, and second, the size of the image at the dividing edge of the reflector *D* of Fig. 4A.

The complete optical system may be reduced to that shown in Fig. 12 by replacing the spherical reflector *B*, Fig. 4A, with a lens of equivalent focal length. The dimensions of the photoelectric recorder optical system are such that the image of the filament must be focused at a point between the mirror *A* and the lens *B* in order to obtain an image at *D*. Fig. 12 is therefore drawn for this condition.

The plane mirrors *A* and *C* are sufficiently large not to act as light stops and they may therefore be neglected from further consideration as far as the size of image and total amount of light are concerned. However, in order that the light from the mirror *A* will strike the mirror *C* throughout the complete scale range, it is necessary that *A* and *C* be placed at conjugate foci of *B*. Thus in Fig. 4A the two instruments need not be coaxial but may be placed anywhere that will satisfy this condition. The various possibilities and the relative advantages of each, need not be considered here.

By means of well known optical formulas the size of the filament image at the dividing edge of reflector *D* may be computed. In terms of the filament dimensions ab_0 the image dimension ab_D is

$$ab_D = \frac{d_1\, d_3}{d_2\, d_4}\, ab_0$$

where d_1, d_2, d_3, and d_4 are the various focal distances.

The total amount of light obtained at *D* may be computed by:

$$I_D = \frac{K\, C_p\, \pi\, d_L^{\,2}}{4\, d_4^{\,2}} \text{ (lumens)}$$

where:

K = The product of the reflecting powers of all the mirrors.

C_p = The candle power of the lamp in the direction of the lens.

d_L = diameter of the lens, *L*.

d_4 = distance from lens, *L*, to lamp filament.

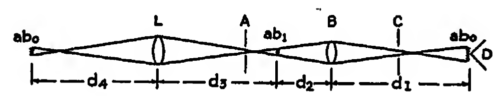


Fig. 12—An Equivalent Optical System

The dividing edge of the mirror *D* may be quite broad so some of the light will be lost there, and less than half of the amount computed from the foregoing equation will actually strike each photoelectric tube.

Discussion

P. E. Twiss: The use of recording instruments has, in the past, been limited to measurements of relatively large values, necessary to obtain the proper torque for producing a record of suitable accuracy and prompt response. The new photoelectric recorder permits of recorded values heretofore measured only by the use of indicating instruments. This opens up a new field of unlimited scope for recording instruments, not only for measurements of low electrical values, but also for many applications of the photoelectric cell in measuring and recording light intensity.

An analysis of the design of this instrument indicates that all component parts are familiar to the trade and have been proven satisfactory by actual service in other applications over a period of years. The photoelectric cell and the amplifying system including the pliotron tube have been in extensive commercial use for several years and their reliability is well known. The indicating and recording apparatus is also of standard design but includes many recent improvements particularly in the chart mechanism.

A recent successful application of the photoelectric recorder to frequency measurement has been demonstrated by a well-known public utility company whose system is regulated by automatic frequency control equipment. The frequency at several points of the system was measured by other recorders of various designs, and operating data over a period of a year have proven conclusively the superiority of the photoelectric recorder.

C. W. Mayott: In May 1930 a photoelectric frequency recorder was installed in our load supervising office at Hartford. This meter being an experimental one had some mechanical defects, all of which have been corrected in the finished product. It was in satisfactory service for approximately a year and one-half and during this period the only replacement was the light source bulb.

The meter gives the much desired instantaneous and continuous record that is so desirable in operation, especially in checking up disturbances. It can give a frequency record in such detail and such magnified scale as to be beyond the requirements of any present operating demands.

H. A. Rolnick: 1. What is the smallest angular motion of the indicating element to which the recorder will respond?

2. Is the above dependent on the electrical circuit or on the optical system or on both?

3. How much difference would a movement of the lamp filament of 0.01 in. to the right or left have on the recorder reading?

C. W. LaPierre: Referring to Mr. Rolnick's questions in the order mentioned:

1. The circuit of the photoelectric recorder is in a position of unstable equilibrium under the balanced condition. Consequently the recording element is responsive to infinitesimal movements of the basic indicating element from balance. This condition would lead to hunting between the recording element and the photoelectric circuit if the tendency were not damped out by the pliotron grid to filament resistance and capacitance (see Fig. 5). The damping capacitance and resistance, however, do not decrease the sensitivity of the circuit—they only make the time of response of the photoelectric circuit the same order of magnitude as the time of response of the recording element.

2. As may be inferred from the answer to question (1), the sensitivity of the response of recording to indicating elements is independent of the optical system and electrical circuit. However, it may be well to repeat that the rapidity with which the recording element responds, is somewhat dependent upon the electrical circuit and optical system. In this answer, I am assuming, of course, that Mr. Rolnick refers to normal variations in the circuit and optical system and not to changes such as would modify the fundamental principles of operation of the circuit.

3. In the design of the photoelectric recorder described in the paper, a sidewise shift in the lamp of 0.01 inch would produce roughly a change in reading of 0.05 per cent of the scale range value. In more recent designs, we have allowed this effect to increase in order to gain other benefits as our experience shows that changes of this order do not occur after a lamp is installed. Any errors at the time of lamp replacement may be completely eliminated by resetting the instrument on zero.

Interconnection of Primary Lightning Arrester Ground and the Grounded Neutral of the Secondary Main

BY C. FRANCIS HARDING[1] and C. S. SPRAGUE[2]
Fellow, A.I.E.E. Associate, A.I.E.E

Synopsis.—This investigation of the relative merits of various possible transformer connections and protective devices was the result of statistical data secured, over a long period of years, by the Commonwealth Edison Company of Chicago regarding the number and types of distribution transformer failures during lightning storms. It refers to standard, 60 cycle, overhead, power and lighting distribution systems having 4,000-volt, four-wire primaries and three-wire, 230-volt, three-phase power and 115-230-volt lighting secondary mains.*

Five spans of standard pole line construction were exposed to transient potentials of steep wave front, the latter being induced by the sudden charging of the well insulated artificial cloud suspended over the line. The cloud was charged to potentials, up to 150 kv., by means of a surge generator. Measurements of potentials, ranging as high as 40 kv. in some instances which were induced upon various portions of the distribution system were made by means of ionized sphere gaps and the cathode-ray oscillograph.

Some of the important conclusions reached as the result of this investigation are:

1. The value of an experimental wood pole distribution line with an insulated artificial cloud charged by means of a surge generator was definitely established for lightning protective investigations involving induced as well as direct stroke potentials.

2. The practicability and economy of studying, by means of such laboratory equipment, the operation of various transformer, lightning arrester and ground connections, when exposed to surges approximating those of lightning, were demonstrated.

3. Efficient primary protection upon an overhead distribution system affords a considerable degree of protection to secondaries located below the primaries.

4. A well grounded secondary neutral wire acts to reduce potentials on adjacent wires.

5. With existing transformer design, the insulation of the secondary winding may be considerably over-stressed by steep wave front surges without excessive stress on the primary insulation. Such secondary stresses may be relieved by improvements in secondary insulation.

6. Low ground resistances, although desirable in other respects, do not necessarily reduce the initial potentials which may be induced upon the system.

7. A non-inductive load in the consumer's premises reduces the potentials 60 to 70 per cent at the service entrance.

8. Tests have shown that the interconnection of primary lightning arrester ground to the grounded neutral of the secondary main effects a considerable reduction in voltages at the transformer and imposes no extra hazard upon the consumer's wiring.

Introduction

Under a cooperative arrangement* with the Utilities Research Commission of Chicago, the Engineering Experiment Station at Purdue University has been conducting an investigation of surge protection of distribution circuits. A considerable number of the tests has involved the interconnection of the primary lightning arrester ground and the grounded neutral of the secondary main. It is this phase of the work which will be considered in this paper.

Description of Apparatus

After some preliminary work, a five-span distribution system was constructed, over which was supported an insulated artificial cloud for the purpose of inducing surge potentials in the distribution system. The latter was composed of four 4,000-volt primaries on the upper arm and six secondaries on the lower arm comprising a three-phase, 230-volt power secondary and a single-phase 115-230-volt lighting secondary. These are of the standard construction of the Commonwealth Edison Company of Chicago. A bank of three distribution type transformers and a customer's service were included in the distribution system but were not connected to any 60 cycle supply. Circuit grounds were made in the customer's service and on the distribution system as in practise. (See Fig. 1 for circuit diagram.)

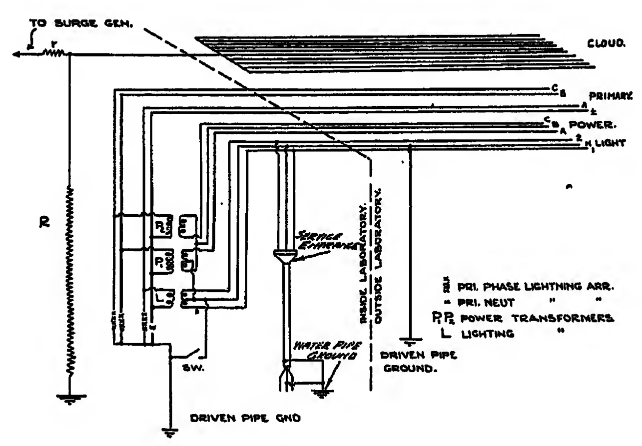


Fig. 1—Circuit Diagram of Cloud, Line, and Transformers

Method of Test

The cloud was normally held at ground potential by means of a high resistance leak. At definite intervals a surge generator† was made to discharge into the cloud,

1. Head of School of Electrical Engineering, Purdue University.

2. Research Assistant, Engineering Experiment Station, Purdue University.

**Studies in Lightning Protection*, by D. W. Roper, A.I.E.E. Trans., March 1932, p. 252.

Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 25-29, 1932.

†"Purdue Builds Lightning Generator," *Electrical World*, January 17, 1931, Vol. 97, No. 3, p. 142.

thereby causing a sudden change in cloud potential with consequent induced voltages in the distribution system. Sphere gap measurements of these induced voltages were taken at the transformers and at the customer's service entrance.

Results of Tests

A series of tests was made in which the induced voltages to ground were measured as the distribution system was built up step by step, that is, starting with the wires only and adding the circuit grounds, arresters, transformer windings, etc., until the complete circuit was obtained.

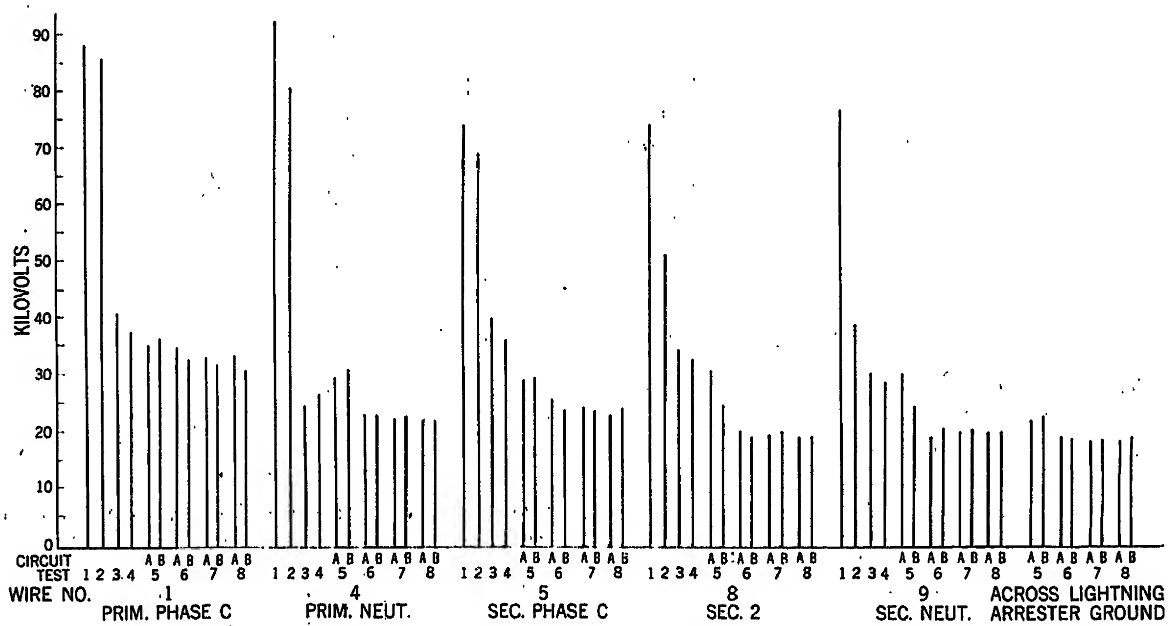


Fig. 2—Induced Potentials to Ground with Increasing Amounts of Apparatus Connected to the System

Induced voltages to ground on distribution wires with the following circuit conditions
Test 1—No apparatus or grounds connected but each wire grounded through high resistance
Test 2—Same as test 1 with secondary neutral grounded one pole from transformer bank
Test 3—Same as test 2 with primary arresters connected
Test 4—Same as test 3 with primary windings connected
Test 5—Same as test 4 with secondary windings connected
Test 6—Same as test 5 with house circuit connected and no load in house circuit
Test 7—Same as test 6 with six 25-watt lamps in house circuit
Test 8—Same as test 7 but with six 100-watt lamps in house circuit
A indicates secondary neutral not connected to primary lightning arrester ground at transformer
B indicates secondary neutral connected to primary lightning arrester ground at transformer

Fig. 2 shows graphically the change in the magnitude of the induced voltages during the above procedure, and also shows the system voltages with and without the interconnection of the secondary neutral to the primary arrester ground. (See Fig. 3 for wire positions on cross arm.)

The graphical presentation of Fig. 2 is, in general, self-explanatory. However, it is desired to call attention to some of the more interesting changes in the induced voltages and their causes. As noted in the legend of Fig. 2, the first line of each group represents the induced voltages on that particular wire with no grounds or connected apparatus. Primary voltages (between wires 1 or 4 and ground) were approximately 90 kv.; secondary voltages (between wires 5, 8, 9 and ground) were approximately 75 kv. Test No. 2 of each group represents the induced voltage when wire No. 9 (sec. neutral) was connected to a driven pipe ground of approximately 15 ohms resistance, one span from the transformer bank. Aside from the reduction in voltage on wire No. 9 itself, it is interesting to note the considerable reduction on wires 4, and 8, adjacent to wire No. 9. (Fig. 3.)

Test No. 3 of each group indicates the voltages with the further addition of primary phase and neutral arresters. As would be expected, there was a marked decrease in all primary voltages. There occurred also a very noticeable reduction in secondary voltages (wires 5, 8, 9) due to the shielding effect of the primary wires after the primary arresters had broken down. The significance and importance of this lies in the fact that it indicates that in the field, a well protected primary system provides a considerable degree of protection for secondaries located below the primaries.

In Test No. 4 the connection of the transformer primary windings caused a very slight reduction in voltage, showing that the primary winding presents a relatively high impedance to the surge.

With transformers, house-wiring circuit, and all

grounds connected to the circuit, (Fig. 1) voltages to ground on the power and lighting secondaries and on the primary neutral were of the order of 20-25 kv., while those between the primary phase wires and ground were of the order of 30-35 kv.

With regard to voltages across transformer windings it was determined that for a single-phase lighting transformer with its secondary neutral grounded the voltage across the secondary winding was approximately 5 per cent to 15 per cent of that existing across the primary winding. With three-phase, 230-volt, delta-connected power secondary windings having the mid-point of one winding grounded to the lighting secondary neutral, it was determined that the voltages across the secondary coils were approximately 20 per cent to 80 per cent of those existing across the power transformer primary windings. Either of these percentages overstress the secondary insulation without exceeding the safe limit on the primary insulation. A solution of this difficulty is to increase the insulation of the secondary winding. In so doing, of course, capacitances between primary, secondary, and core will be changed. Consideration should therefore be given to the redistribution of potentials resulting therefrom. These are relatively inexpensive additions to the design and construction of the transformer.

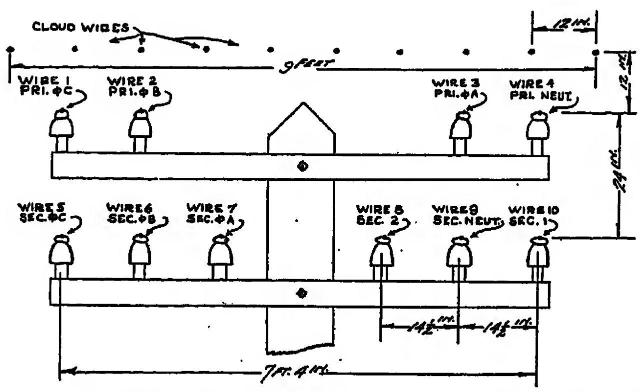


FIG. 3—CROSS SECTION OF CLOUD AND LINE SHOWING WIRE POSITION

In the preceding group of tests the interconnection of the secondary neutral and the lightning arrester ground caused, in general, approximately 5 per cent decrease in the magnitude of the induced voltages to ground.

Throughout most of the work, tests have been made with and without the secondary neutral wire connected to the primary lightning arrester ground lead. The tests indicated that the effect of this connection depends to a large extent upon such factors as the steepness of wave front and the time lag of the primary arresters, hence no definite statement can be made to the effect that this connection is always beneficial. The connection of the lighting secondary neutral to the lightning arrester ground caused 10 per cent reduction in the voltages at the service entrance.

Figs. 4 and 5 portray graphically the magnitudes of the induced voltages at the transformers and at the service entrance under various conditions of ground resistances, and with and without the interconnection of the secondary neutral to the primary lightning arrester ground. In several instances this interconnec-

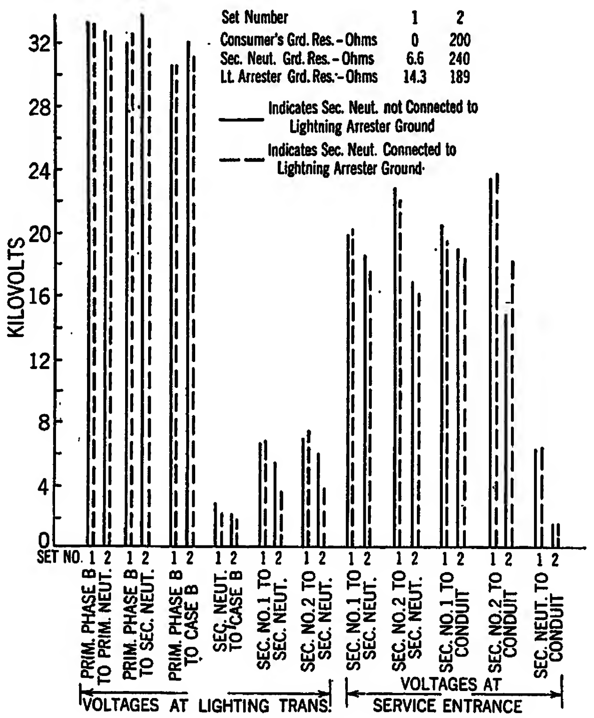


FIG. 4

Induced voltages at lightning transformer and service entrance with secondary neutral ground one span from transformer pole

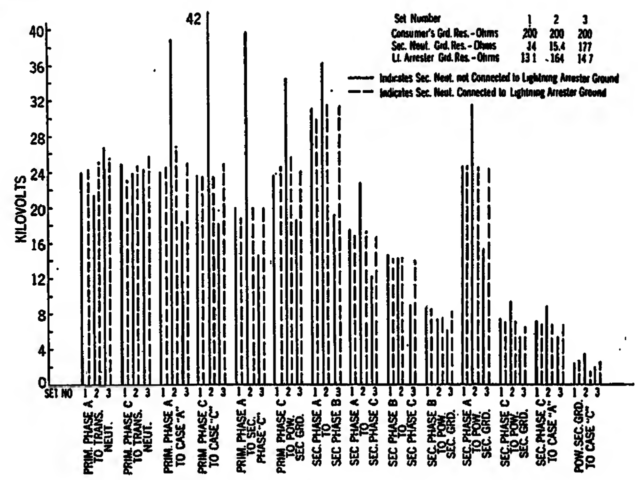


FIG. 5

Induced voltages at power transformers with secondary neutral ground at transformer pole

FIGS. 4, 5—EFFECT OF INTERCONNECTION ON THE POTENTIALS AT THE TRANSFORMERS AND AT THE SERVICE ENTRANCE WITH VARIOUS GROUND RESISTANCES

tion caused a material decrease in the voltage between primary phase wire and secondary ground.

Field investigations have demonstrated that a very considerable number of transformer failures and cases of fuse-blowing have occurred by flash-over from the

primary phase lead to case and thence to secondary neutral. In fact, operating companies have reported that in about 75 per cent of the transformer failures on distribution systems due to lightning, the damage involved both the primary and secondary windings. Measurements of the voltage between primary phase lead and secondary neutral have shown that the *interconnection of the secondary neutral with the lightning arrester ground is, in general, beneficial to the transformer.* In particular, with a low resistance secondary neutral ground and a high resistance lightning arrester ground, the interconnection reduced the above voltage by 30-50 per cent. (See Fig. 5, Set 2.) With no interconnection and a high resistance secondary neutral ground and a low resistance lightning arrester ground, the voltage between primary phase lead and secondary winding was somewhat reduced at the expense of an increased voltage across the high resistance secondary neutral ground. With the addition of a low resistance ground to the secondary neutral by making the above interconnection, thus placing the high and low resistance grounds in parallel, a redistribution of voltage occurred such that the potential between primary phase lead and secondary neutral was approximately the same as with the interconnection in the case of low secondary neutral ground resistance and high lightning arrester ground resistance. (See Fig. 5, Set 3.)

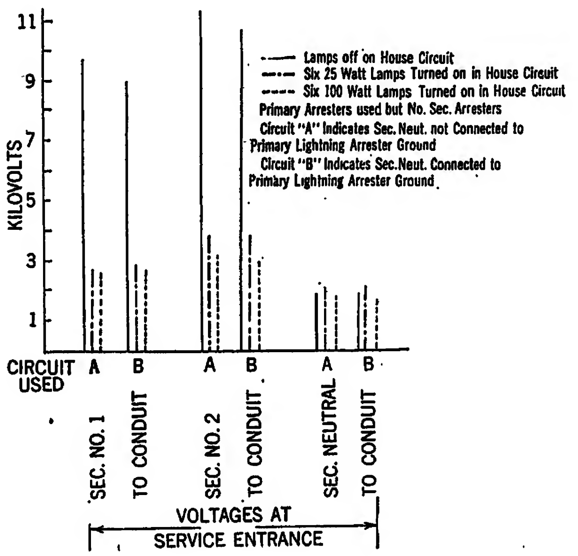


Fig. 6—Effect of Lamp Load on Voltages at Service Entrance

Induced voltages at service entrance

Fig. 6 shows a 10 per cent reduction in the potentials at the service entrance due to making the interconnection. There is indicated a very considerable reduction in the voltages at the service entrance when the customer's lamps were turned on. This seems to be an argument in favor of turning on the lamps during a thunderstorm.

During the latter part of the work the transformers were mounted on the pole and a testing shelter was constructed as in Fig. 7. The induced potentials were slightly higher but otherwise were in good general agreement with those obtained when the transformers were on the laboratory floor. The majority of the work presented here has been done with the transformers on the poles.

Acknowledgment is gratefully extended to the Utilities Research Commission for the opportunity to work

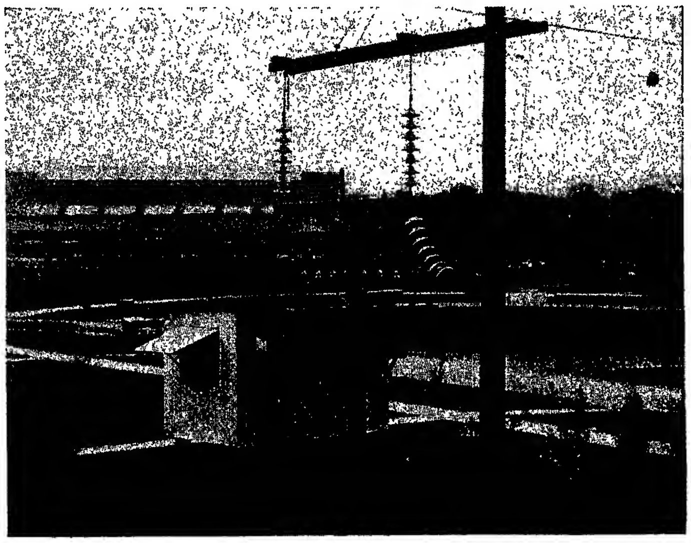


Fig. 7—View of Outdoor Transformer Installation and Testing Shelter

on this interesting problem. The authors also wish to express their appreciation for the encouragement and valuable suggestions and advice received from the Committee, Mr. D. W. Roper, Chairman, supervising the work for the Commission. Also to Messrs. J. S. Malsbary and H. Creviston of the engineering staff and to students who have assisted in the routine testing, we express our thanks.

Conclusions

1. The value of an experimental wood pole distribution line with an insulated artificial cloud charged by means of a surge generator was definitely established for lightning protective investigations involving induced as well as direct stroke potentials.

2. The practicability and economy of studying, by means of such laboratory equipment, the operation of various transformer, lightning arrester and ground connections, when exposed to surges approximating those of lightning, were demonstrated.

3. Efficient primary protection upon an overhead distribution system affords a considerable degree of protection to secondaries located below the primaries.

4. A well grounded secondary neutral wire acts in reducing potentials on adjacent wires.

5. With existing transformer design, the insulation of the secondary winding may be considerably over-

stressed by steep wave front surges without excessive stress on the primary insulation. Such secondary stresses may be relieved by improvements in secondary insulation.

6. Low ground resistances, although desirable in other respects, do not necessarily reduce the initial potentials which may be induced upon the system.

7. A non-inductive load in the consumer's premises reduces the potentials 60 to 70 per cent at the service entrance.

8. Tests have shown that the interconnection of primary lightning arrester ground to the grounded neutral of the secondary main effects a considerable reduction in voltages at the transformer and imposes no extra hazard upon the consumer's wiring. Specific cases of this conclusion are as follows:

a. With the lightning arrester ground resistance and secondary neutral ground resistance below 20 ohms, the interconnection mentioned above has very little effect upon the magnitudes of the potentials at the transformer.

b. This interconnection causes a 30-50 per cent reduction in potentials across the transformer in the case of an arrester ground of 100 to 200 ohms and a secondary neutral ground of less than 20 ohms.

c. With a lightning arrester ground of less than 20 ohms and a secondary neutral ground of from 100 to 200 ohms, the potentials across the transformer were increased about 25 per cent by making this interconnection.

d. With secondary neutral and primary arrester ground resistances both ranging from 100 to 200 ohms, the interconnection had practically no effect upon the magnitudes of the voltages at the transformer.

9. With the usual city conditions consisting of a multiplicity of low resistance grounds on the secondary neutral and the further possibility in some instances of a lightning arrester ground of high resistance, it has been demonstrated herein that potentials at the transformer may be greatly reduced by the interconnection of the primary lightning arrester ground and the grounded neutral of the secondary main.

Discussion

For discussion of this paper see page 271.

Lightning Protection for Distribution Transformers

Field Studies of Lightning Arrester Protection, Including the Effect of Interconnection

BY K. B. McEACHRON*
Member, A.I.E.E.

and

L. SAXON†
Non-member

Synopsis.—A cooperative field study with portable impulse generator and cathode ray oscillograph was made of the lightning protection of transformers connected to a 4.45-mile 4,600-volt rural distribution circuit. The tests described were made with the pellet arrester. Some of the conclusions are:

1. Although the arrester discharge voltage is but a fraction of the strength of the transformer, yet for the usual connection to ground now commonly employed, arrester ground resistances may be high enough so that the transformer is not protected, resulting in either blown fuses or a winding failure.

2. Interconnection of the primary arrester ground and secondary neutral gives a high degree of protection to the transformer from surges originating on either primary or secondary regardless of the arrester ground resistance.

3. The interconnection of primary arrester ground and secondary neutral does not increase the magnitude of voltages which appear between various grounded objects on the consumers' premises over that now experienced with exposed secondary conductors and possible bushing flashovers or transformer failure. The effect of the interconnection is to increase the number of impulses reaching the secondary circuits but not their magnitude.

* * * * *

EXPERIENCE has shown that although failures of distribution transformers and fuse blowing during lightning storms are greatly reduced by the application of lightning arresters, yet the record of protection is not as good as the strength of the transformer and performance data of the arrester indicate that it should be. The ratio between the transformer strength and the voltage allowed by an arrester such as the pellet is not far from four to one. With such a large margin, failures of transformers or fuse blowing due to lightning should be practically eliminated, except in the case of direct stroke at the transformer location which is a relatively infrequent source of trouble.

In protecting apparatus against the effects of lightning it is recognized that differences of potential must exist to cause failure. If flashovers or punctures which result in follow current can be eliminated most of the fuse blowing due to lightning will be eliminated. The problem to be solved, therefore, is one of preventing excessive differences of potential from developing between different parts of the transformer. Whether the potential to which the transformer is held be ground potential or the potential of the lightning surge, makes little difference as far as the transformer itself is concerned.

In the past it has been common practise, with a very few exceptions, to connect the primary lightning arresters to a driven ground at the base of the transformer pole, with the idea that the lightning entering over the primary would pass to ground thus holding the primary winding to a potential equal to the arrester discharge voltage. Unhappily this condition is seldom met in practise as arrester ground resistances are not zero and may be as high as several hundred ohms. Lightning frequently enters over the secondary conductors and the arresters connected to the primary are then not in a position to be of service. Indeed the exposure of secondary circuits in urban districts may considerably exceed that of the primary conductors. Thus it is clear that there are several factors which operate to prevent the primary arrester from holding the windings at substantially ground potential.

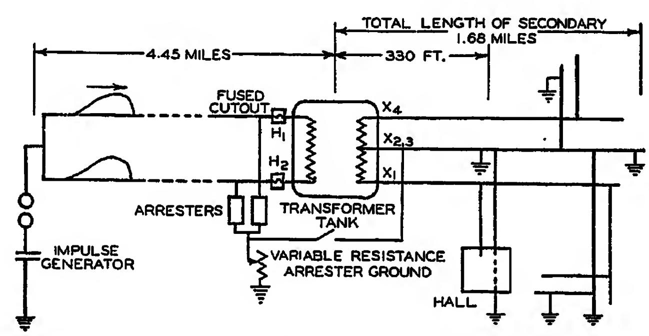


FIG. 1—CIRCUIT CONNECTIONS OF PROTECTION TEST ON TRANSFORMERS

There has been a growing conviction on the part of those closely associated with the problem of protection, that the present method of arrester application is at the mercy of too many uncontrollable factors in practise. Connecting the primary lightning arrester ground to the grounded secondary neutral appears to eliminate many of the uncontrollable factors. With such a connection the voltage between the transformer windings under impulse conditions will not exceed the potential allowed by the arrester, which is so low that flashover of the bushing or failure of the transformer should be

*General Electric Company, Pittsfield, Mass.
†Utility Management Corporation, New York, N. Y.
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practically eliminated. In proposing such a scheme the question naturally arises: will such a scheme introduce additional hazard on the customer's premises and will it offer the advantage from the protection standpoint which it appears that it should? Experience in those cases where this interconnection has been tried does not indicate any increased hazard, and the protection record seems to be far above that of the present connection.

In order that experimental data might be obtained under controlled test conditions, the General Electric Company has been conducting a field investigation in cooperation with the Associated Gas and Electric Company. The tests were made on a single-phase 4,600-volt rural line of the New York State Electric and Gas Company, built to serve the village of Willseyville, N. Y. and the surrounding community. The line had just been constructed at the time the tests were made and for most of the power tests, to be described, was energized at 2,300 volts. The portable million volt impulse generator and the cathode ray oscillograph were used in the test. A positive impulse voltage of 350 kv. applied resulted in a 6/14 microsecond wave with a crest of 123 kv. at the test transformer location 4.45 miles away. It was necessary to materially increase the insulation at most of the guyed poles to prevent flashover.

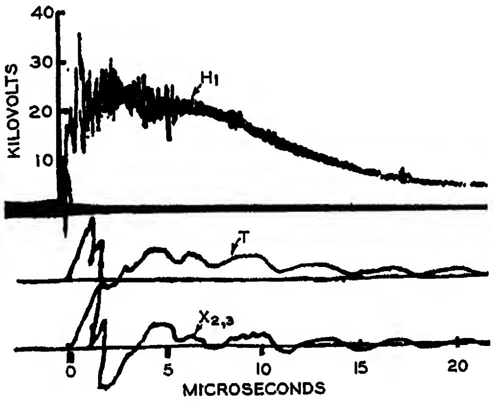

Fig. 2—Standard Connection. Impulse Applied to Primary. Arrester Ground Resistance 10 Ohms

H_1 Primary to ground
T Tank to ground
$X_{2,3}$ Secondary neutral to ground
All oscillograms have the same calibration

A 10-kva. 2,300-115/230-volt transformer was mounted on pole No. 48 about 30 ft. above ground. The primary conductors terminated on this pole. The three secondary conductors X_1, $X_{2,3}$ and X_4 extended from this pole into the village of Willseyville, having a total circuit length of 3,273 ft. located on four streets. A building which will be designated as the "hall" was connected between X_1 and $X_{2,3}$ at a point about 400 ft. from pole No. 48. This building was the only one connected to the secondary circuits during the tests. In addition to the 65-ohm ground at the hall the secondary neutral was grounded at five points, the nearest being about 330 ft. from pole No. 48. The combined resistance of all secondary grounds was 25 ohms.

The hall was wired with BX and had a measured capacitance of 0.04 μf. between one wire and ground. It was provided with six circuits and twenty-six outlets. The hall ground was made to the casing of a driven well. The service meter had not been installed.

All cathode ray oscillograms registered voltages to ground. Voltages between windings are obtained by subtraction, which were checked by direct measurements with sphere gaps. Resistance and capacity dividers were used to reduce the potentials to proper values for the oscillograph deflecting plates.

The tests were made mostly with 3-kv. pellet arresters which have a breakdown potential of about 17 kv. and an IR drop of 6 to 7 kv. according to laboratory tests. Some of the tests were made with higher rated pellet arresters.

Protection Tests

Only results with impulses on both primary conductors will be given as this is the most representative condition of service and the conclusions drawn from the work apply equally well whether the impulse is on one conductor or both. Although nearly 1,000 oscillograms were taken, in the limited space available only a fractional part of the data can be shown.

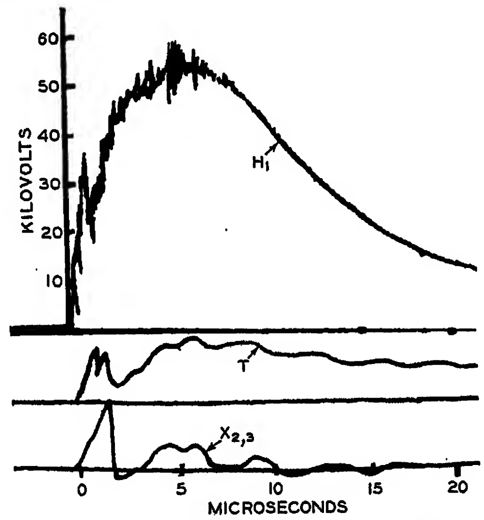

Fig. 3—Standard Connection. Impulse Applied to Primary. Arrester Ground Resistance 60 Ohms

All oscillograms have the same calibration

Impulse Applied to the Primary

Oscillograms given in Fig. 2 show the potential with respect to ground of the primary H_1 tank T and secondary neutral $X_{2,3}$ with the 3-kv. primary arresters connected to a 10-ohm ground in the usual manner. The secondary neutral potential remains close to ground while the tank takes an intermediate potential, but close to the secondary. As a result most of the potential allowed by the primary arrester and its ground is impressed from the primary to tank and secondary.

Increasing the arrester ground resistance to 60 ohms increases the primary potential to tank and secondary

and also increases the tank potential, as shown in Fig. 3. It is clear that further increase in arrester ground resistance is likely to result in either flashover of the primary bushings or a winding failure. Flashover of both primary bushings, or cascade flashover of a primary and secondary bushing if the primary is grounded is likely to result in blown fuses.

Interconnecting the arrester ground and secondary neutral greatly reduces the potentials between windings and from winding to tank, as shown in Fig. 4. With this connection the oscillograms show that the tank and

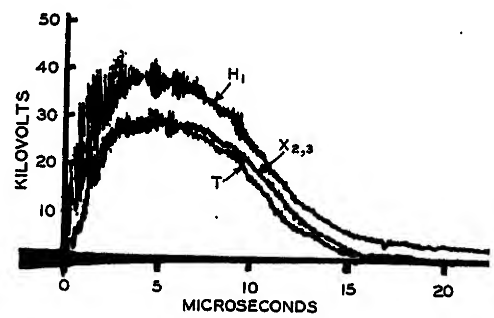

Fig. 4—Interconnection. Impulse Applied to Primary. Arrester Ground Resistance 60 Ohms

secondary have practically the same potential, while the primary to secondary potential is only the arrester potential, although the arrester ground resistance was 60 ohms.

In Fig. 5 the oscillograms of Figs. 3 and 4 are subtracted to show the great reduction in potential between primary and secondary when using the interconnection. Fig. 6 shows that there is very little difference of potential between the different windings even with the arrester ground disconnected. Thus, regardless of the arrester ground resistance the transformer is well protected and fuse blowing will be reduced to a minimum by eliminating bushing arcover.

Impulse Applied to Secondary

In making this test the line conductors from the impulse generator were connected to the two secondary wires X_1 and X_4, each of the primary leads of the transformer being connected to ground through a 500-ohm surge impedance. As in the previous protection tests the entire secondary distribution was connected but with no lights on at the hall. The standard arrester, with a ground resistance of 19 ohms shows a high voltage between primary and secondary, Fig. 7, which is greatly reduced by the interconnection even though the arrester ground was disconnected, Fig. 8, just as in the case of impulse on the primary. Thus the primary arrester with interconnection will keep the windings at potentials differing only by the arrester potential, whether the impulse originates on primary or secondary. In the case of extremely steep waves originating on the secondary, secondary protection between conductors and neutral may be indicated.

Grounded Tank

Tests made using 6-kv. pellet arresters with and without the tank connected to the arrester ground, which had a resistance of 10 ohms, are shown in Fig. 9. The oscillograms are replotted as they were originally taken with different time scales. The impulse was applied to both primary conductors, the secondary conductors still being connected to the secondary distribution system. The results show that the connection of the tank to the arrester ground lowers the potential between the primary and tank to the arrester voltage, but raises the potential between the tank and secondary to a value equal to the *IR* drop in the ground. Such connection does not lower the voltage between primary and secondary, and if the ground resistance is high, excess potentials will appear between the tank and secondary.

Measurements at the Hall

Oscillograms were taken at the hall during the protection tests and the maximum voltage was found to be 3.9 kv. At this potential sparking took place within fixtures which effectively limited the voltage. With the standard arrester connection on pole No. 48 and an impulse of 123 kv. applied to the primary, the potential between conductors at the hall was 400 and 880 volts when the arrester ground resistance was 10 and 60 ohms respectively. When a gap between primary and secondary set for about 50 kv. r.m.s. sparked, the hall wiring arced over at 3.9 kv. When the interconnection between primary arrester ground and secondary neutral

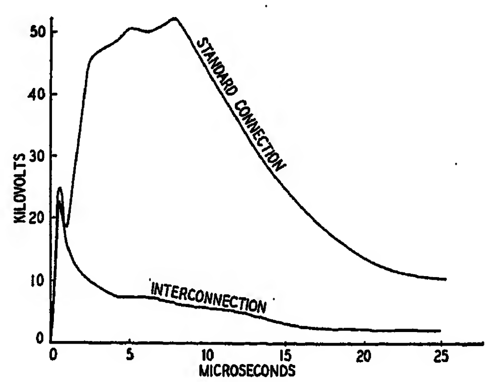

Fig. 5—Standard and Interconnection Compared

Voltages from primary to secondary neutral. 60-ohm arrester ground

was made the wiring arced over even with arrester ground resistances as low as 10 ohms.

With the interconnection, the impulse being applied to the secondary conductors, and the arrester ground disconnected at pole No. 48, the wiring arced over and a potential of 15 kv. was measured to a separate ground at the hall. With a 100-watt lamp connected across the secondary, the potential between wires was reduced to 1.3 kv.

Power Tests: Isolated-Neutral Power Supply

Two transformers rated 1½ kva. which had blown fuses quite consistently during lightning storms were placed on pole No. 48 fused with 2 ampere fuses. A 25-ampere non-inductive load was connected to X_1 and X_4. The primary voltage was 4,600 non-grounded, which was obtained from a rural 6,900 single-phase line through the use of two 50-kva. transformers rated 6,900/2,300 and 2,300/4,600, respectively.

Transformer No. 1 which had low oil level sparked over the terminal board with power follow which blew the 2-ampere fuse. With 6-kv. pellet arresters connected and ground resistances up to 170 ohms the terminal board did not flash and of course the fuses did not blow. The oil level was raised, arrester disconnected, and ten impulses applied, which arced to the tank over both the primary and secondary leads. No power follow took place, which was to be expected since the power source was not grounded.

The second transformer did not arc over even with arrester ground resistances as high as 170 ohms. The arresters were then removed and both high-voltage bushings arced over to the tank. Although ten impulses were given, some with and some without secondary 28 ampere load, the primary 2 ampere fuses did not blow. A more intense discharge might have started the power follow. When these tests were made the time was so limited that it was impossible to vary conditions until power follow did take place.

During the tests with the primary ungrounded oscillographic measurements at the hall showed no increase in power voltage either between wires or to ground. Likewise with the same power source the interconnection of arrester ground and secondary neutral did not give any power voltage at the hall during the period of arrester operation.

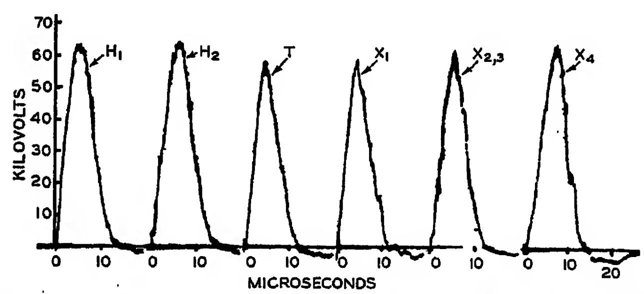

Fig. 6—Interconnection. Primary Arrester Ground Disconnected. All Voltages Shown

Grounded Primary

The 10-kva. transformer on pole No. 48 was connected to the secondary distribution, its primary receiving power over the experimental line at 2,300 volts from one of the 50-kva. transformers connected to the 6,900-volt rural line. For the tests to be described one conductor was grounded through a 35-ohm ground at the 50-kva. transformer, to simulate one leg of a 2,300/4,000-volt grounded neutral system.

Fault Between Primary and Secondary

A ¾-inch gap was connected between the primary phase wire and the secondary neutral. Four impulses out of five blew the 2-ampere fuse on power follow, a voltage of between 600 and 750 volts effective being measured between the conductors and a separate ground for times up to about one-half second until the fuse cleared the circuit. With a lower resistance ground at the power source the voltage measured at the hall would have been higher but the duration shorter.

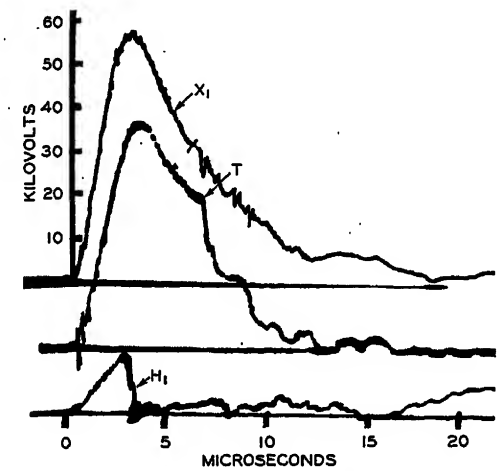

Fig. 7—Standard Connection. Impulse Applied to Secondary. Arrester Ground Resistance 19 Ohms

All oscillograms have the same calibration

Tests with Interconnection—Voltages at the Hall

With the 3-kv. arrester disconnected from ground at pole No. 48, but with the interconnection, a voltage of 101 volts r.m.s. was measured for a fraction of one cycle. The secondary neutral ground was 25 ohms and the primary ground at the 50-kva. transformer, 35 ohms.

When the primary arresters were connected to a 10-ohm ground at pole No. 48 the potential of the conductors at the hall to a separate ground was 33 volts r.m.s. for a fraction of a cycle.

Another test was made in which the sheath of the *BX* conduit was connected to a separate ground from that of the grounded conductor within the conduit. With interconnection, and an arrester ground on pole No. 48 of 10 ohms, and secondary ground of 25 ohms, no 60-cycle potential could be measured to a separate ground, although the sheath ground was of the order of 1,000 ohms. Between the sheath and the grounded conductor a potential of 33 volts would undoubtedly have been measured for this condition.

Conclusions

1. With the present connection primary arrester ground resistances play an all important role in the protection afforded by the arresters, and a ground resistance which may not be too high for one discharge may be totally inadequate for a higher current discharge.

Since low ground resistance is expensive and frequently cannot be obtained, efficient protection requires the use of some method to eliminate the variable effect of ground resistance.

2. Impulses originating on the secondary network cause the tank potential to rise above the primary and a primary failure may result—although the entrance was secondary. Thus some failures charged to primary entrance may have been due to secondary entrance.

3. Grounding the tank to the arrester ground is not particularly helpful as it reduces the primary to tank stress to the voltage allowed by the arrester, but increases the secondary stress by the *IR* drop in the ground.

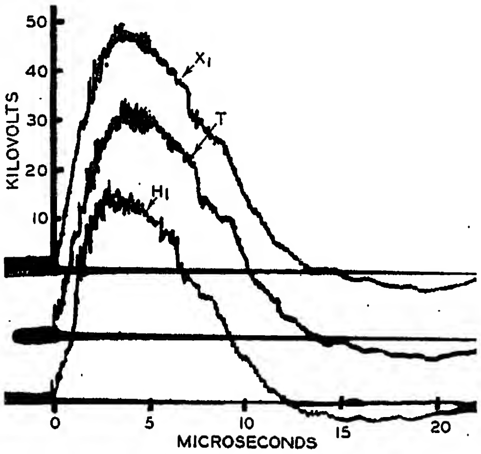

FIG. 8—INTERCONNECTION. IMPULSE APPLIED TO SECONDARY. ARRESTER GROUND RESISTANCE INFINITY

All oscillograms have the same calibration

4. The interconnection of primary arrester ground and secondary neutral will reduce the potential during lightning discharges to the voltage allowed by the arrester, whether impulses come from the secondary or primary circuits. Transformers in reasonably good condition should not fail due to lightning, nor should fuses blow except in case of severe direct stroke very close to the transformer location. Thus accidental connection between primary power supply and customer's premises should be practically eliminated.

5. The potential allowed on the transformer by the arrester with interconnection is independent of the arrester ground resistance so that the transformer is protected whether the arrester ground resistance is high or low.

6. Nothing is to be gained with the interconnection by connecting the transformer tank to the secondary neutral, since with the tank floating, the potentials developed to tank are much less than the strength of insulation involved and the hazard to linemen is decreased.

7. Interconnection of primary arrester ground and secondary neutral allows impulse current to flow into the secondary network, the amount depending on the arrester ground at the transformer. The tests showed that even a 10-ohm ground did not prevent flashing some of the small gaps which exist in the secondary house wiring. Lightning discharges which originate on the secondary do the same thing and interconnection increases the number of such discharges by the amount of exposure added. If a good arrester ground is used the severity of discharge in the secondary circuits will be much reduced. It is not believed that the increases in the number of discharges represent any increased hazard where the secondary neutral is connected to water pipe grounds, as in cities, even if the arrester is not grounded at the transformer. In rural distribution interconnection may represent some increase in hazard if several different grounds exist within consumers premises so that potential differences may be experienced between different grounded objects and the secondary circuits.

8. From the standpoint of hazard due to power voltage, the present situation is that in many cases of fuse blowing which may or may not have resulted from the transformer failure, power voltages of considerable magnitude appear between the secondary ground and separate grounds on the customer's premises until the fuse blows which may take the time of many cycles, depending on the magnitude of the fault current. With good grounds on the secondary this time will be short and the voltage low, with poor grounds the time is longer and the voltage higher.

9. With the interconnection it is believed that contacts between primary and secondary caused by lightning will be largely avoided thus materially reducing any hazard which may have existed before in those cases where the secondary ground resistance was high. In such cases the arrester should probably be connected to a ground at the point of interconnection into the secondary neutral.

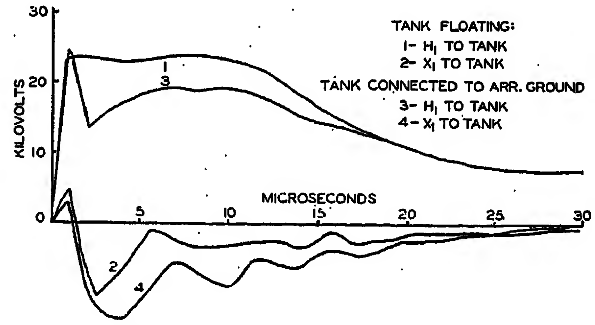

FIG. 9—STANDARD CONNECTION

Potentials between primary and secondary to tank. Tank floating and tank connected to arrester ground. 6-kv. arrester, 10-ohm ground

10. The tests indicate that the record of arrester protection to distribution transformers, including fuse blowing, can be greatly improved by the use of interconnection, providing proper precautions are taken for those cases where the secondary neutral ground is not a water pipe ground. The tests show that arrester

grounds are not necessary where the secondary ground resistance is low as with waterpipe grounds.

11. The results of these investigations should be brought to the attention of those responsible for the various codes so that the benefits of interconnection may be fully realized.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to Mr. E. J. Wade who conducted the test with the assistance of Messrs. D. D. MacCarthy and M. F. Beavers of the General Electric Company and E. H. Emerson of the Power Company. The authors also wish to thank Messrs. P. L. Chambers and C. B. Signor of the New York State Electric and Gas Corporation for their co-operation in placing the line and the equipment at the disposal of the investigators.

Discussion

For discussion of this paper see page 271.

Lightning Protection for Distribution Transformers

BY A. M. OPSAHL*, Associate, A.I.E.E.
A. S. BROOKES,† Associate, A.I.E.E.
and R. N. SOUTHGATE† Associate, A.I.E.E.

Synopsis.—Usual methods of connecting arresters for the protection of distribution transformers are often inadequate. In service some transformers still flash over although the arrester, in itself, is capable of protecting the transformer with a large margin of safety.

Surge current flowing to ground through the ground lead of the arrester gives rise to inductive drop and resistance drop voltages. These voltages added to that permitted by the arrester can be great enough to flash over the transformer bushings to secondary neutral.

By interconnecting the ground lead of the arrester and the transformer secondary neutral, the voltage across the transformer insulation is limited to that permitted by the arrester alone.

Tests have been made to determine the conditions of surge required to duplicate flashovers that occur in practise. Under such conditions measurements were made of the voltages appearing on a representative secondary circuit when bushing flashovers are permitted, and when flashover is prevented by interconnecting the arrester ground and the transformer secondary neutral.

General

ALTHOUGH the low-voltage distribution transformers have a very high impulse strength as compared to the normal voltage rating, they will still flash over and fail in service even when they are protected by arresters which in themselves could adequately protect the transformer insulation. The effect of arrester ground resistance alone is insufficient to account for these failures, as very low grounds still permit failures.

Lightning surges in the common 2,300-volt, or higher, urban distribution circuits manifest themselves in a somewhat different manner from those on high-voltage transmission lines. In the case of a distribution circuit, the arrester spacing will be usually of such order that the distance traveled by the voltage wave will be short, the crest voltage appearing on the line will be limited, and the surge will manifest itself as current through one or more arresters. The current wave, both as to magnitude and shape, is determined very largely by the lightning stroke, and very little by the characteristics of the distribution circuits.

On rural lines the exposure between arresters is much greater and so in addition to surges originating near the arrester there will be surges arriving over a length of line and these voltage surges will be limited by the insulation of that line.

Nature of the Circuit Connections Commonly Used

The protection commonly used for a single-phase house lighting transformer provides for phase and neutral arresters on the primary side connected to a common ground lead down the pole. These arresters may be identical or the neutral arrester may be a simple gap. The ground lead is connected to a ground rod that may have a resistance to earth of five to several hundred ohms.

*Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

†Public Service Electric & Gas Co., Newark, N. J.

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The case of low-voltage class distribution transformers is left free, for the safety of the workman who may touch it while working on the live primary conductors.

The secondary neutral is grounded at each customers service entrance. This ground is made to the water service pipe as it is as good a ground as can be obtained. In addition to the customers ground, there is usually a driven ground at a distance of one span from the transformer.

The Effect of Arrester Ground Circuit on the Protection Afforded

Tests show that when a surge is applied to the primary of a distribution transformer that has a secondary ground, the isolated case will take on a low electrostatic potential above ground so that some 80 to 95 per cent of the surge voltage will appear from primary lead to case. For simplicity in the considerations that follow it will be assumed that the case takes on a potential the same as that of the secondary neutral.

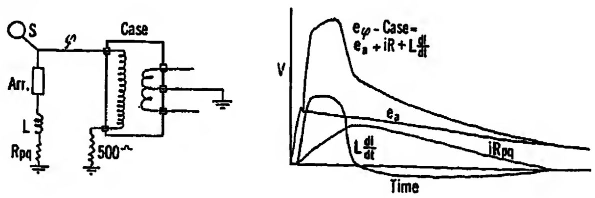

FIG. 1—VOLTAGE ACROSS TRANSFORMER BUSHINGS SHOWN AS THE SUM OF THE ARRESTER VOLTAGE, THE GROUND LEAD INDUCTIVE DROP, AND THE GROUND IR DROP

The voltage across the transformer, as shown in Fig. 1, is the total of three components; the IR drop across the ground, the inductive drop across the ground lead, and the voltage across the arrester. The drop across the ground is proportional to the amount of current in the surge, and the drop across the lead to the rate of rise of current. For anticipated surge currents, the voltage across the ground alone can exceed the voltage across the arrester, unless the ground resistance is of very low magnitude.

Under present methods of construction, the voltages appearing across the primary bushings are often great enough to cause flashovers. The completed path for the surge current to ground is usually over the secondary bushings. Fig. 2 shows the sequence of events during a flashover and the voltages which occur. Primary bushing flashover takes place at a time t_1, and secondary bushing flashover almost simultaneously at a time t_2. With power on the transformer, the flashover path will carry the power arc until the primary fuse opens the circuit. In service this is the path over which the arc burns are usually found.

Under these conditions both the surge current and the power follow current flow through the secondary neutral ground but operating experience seems to show that there is no serious trouble on the customer's property.

Interconnection of the Primary Arrester Ground and Secondary Neutral

By interconnecting the arrester ground and the transformer secondary neutral at the transformer, the potential difference across the primary bushing of the

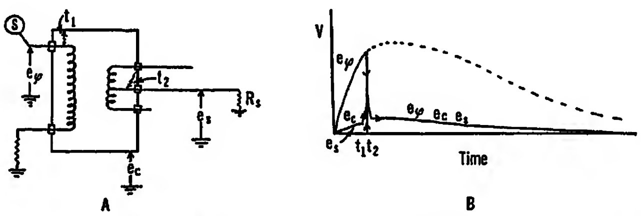

Fig. 2—Successive Flashovers of Primary and Secondary Bushings, and Resultant Potentials

transformer will be limited to that voltage permitted by the arrester alone during a discharge, in accordance with the prior assumption that the secondary neutral and case remain at the same potential. In Fig. 3 is shown the effect of this interconnection where the assumed secondary neutral impedance to ground is very small. Whether or not this secondary impedance is low, the voltage difference appearing across the primary bushing will not be greater than that permitted by the arrester alone.

Under these conditions, the transformer will not flash over and there will be no power current flowing into the secondary neutral from the primary circuit. Whatever impedance drop there is for the surge current flowing in the secondary neutral will appear as voltage in this circuit.

If a solid connection is not permissible between the secondary neutral and the ground terminal of the primary arrester, a gap or valve arrester of a low voltage rating may be placed in the interconnection as shown in Fig. 4A. This arrester will begin taking current when the voltage across the ground lead becomes great enough to discharge the arrester. In this case, the voltage across the primary bushing is the sum of the voltages appearing across the primary and interconnecting arresters as shown in Fig. 4B. This connection will effectively isolate the arrester ground and the secondary neutral as there is no voltage difference between them except during a surge discharge.

A second method of getting improved protection afforded by the interconnection without connecting a solid conductor between the arrester ground and the secondary neutral, is that shown in Fig. 5. Where the effective leakage reactance between the two halves of the secondary winding is small, the surge current in

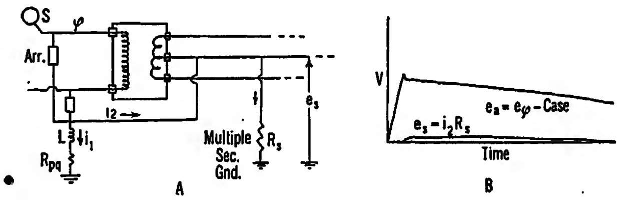

Fig. 3—Voltage Across Transformer Bushings with Connection of Arrester Ground Lead to Secondary Neutral

flowing as indicated will result in a very low voltage across the winding as the magnetic effects of the two currents are in opposition. This circuit was proposed by Mr. C. B. Wright of the Duquesne Light Company and very promising laboratory tests were run in January 1931.

Policy of Interconnecting Primary Arrester and Secondary Neutral Ground

At the present time the safety code forbids the interconnection of the primary arrester and the secondary neutral ground. This regulation was made in recognition of the fact that when a surge current flows through a ground a surge voltage appears across it.

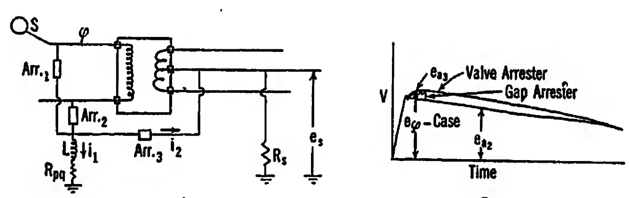

Fig. 4—Voltage Across Transformer Bushings with Connection of Primary Arrester Ground Lead to Secondary Neutral through Low-Voltage Arrester

The driven grounds which were assumed in this case are usually of considerable resistance as compared to the water-pipe grounds which are customary at the present time.

The Limitations of the Policy of Interconnecting Grounds

Where both the primary ground and the secondary ground are driven grounds as in the case of a rural customer, the interconnection can prevent flashover of the transformer insulation but an appreciable surge voltage may appear from secondary to ground. This

condition is less serious than permitting a power fault into the secondary circuit, but both grounds should be made as low as possible so that the *IR* drop may be low.

The ungrounded secondary is not the common practise in distribution circuits. Where it is used, a surge voltage on the transformer primary will give the secondary circuit a potential above ground. The smaller the capacity of the secondary to ground, the greater will be its potential. Obviously an interconnection of a poor primary ground with the free secondary will not appreciably lower the voltage across the

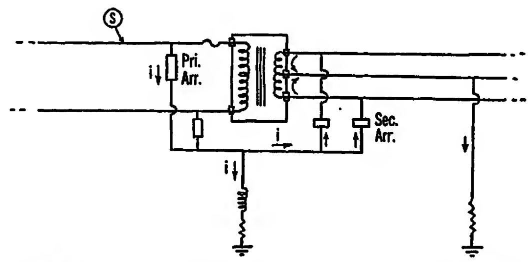

Fig. 5—Path of Current Flow to Ground for Surge Originating on Primary Phase Wire

arrester ground and flashovers from secondary to ground would be expected.

Tests Made on a Representative Distribution Transformer with Secondary Services

In order to determine the magnitude of the effects required to cause flashovers similar to those which have occurred in service, a program of tests was carried through. A diagram of the test circuit is shown in Fig. 6. A distribution transformer was mounted on a 35-ft. pole. A ground lead was provided down the pole and two ground rods were driven at the foot of the pole in order to get as low a resistance as possible. The secondary wires were racked for about 140 feet. From the transformer pole and from the end of the secondary rack, triplex services were run to a point on the ground. Here the neutral wires were solidly grounded. One wire of each triplex service was left open and is indicated on the figure as "open service." One service wire and the neutral from each service were connected to a 100-foot section of two-conductor *BX* cable, both ends of the sheath being grounded. The two sections of *BX* cable were connected to the same two secondary wires.

In the tests as made, flashovers were necessary in order to simulate the conditions that occur in practise. In order to secure consistent flashovers, gaps were placed around the primary and secondary bushings as shown in Fig. 6.

A 500 ohm resistor was placed between the primary neutral and ground to simulate the effect of an uncharged conductor.

The arresters used in these tests were 3,000-volt auto-valve arresters of the disk and mica spacer type. This type of arrester was selected rather than the porous block type because a larger number is in service and the tests were laid out to duplicate service experience as closely as possible. This type of arrester on test had a maximum voltage of 15 kv. crest across its terminals during a surge discharge of 800 amperes.

Most of the oscillograms have been replotted to the same scale in order to show the relative voltage-time values more readily. Successive test surges were found to be very nearly identical. In Table I the crest voltages measured at certain points are tabulated for the various circuit connections and for each of the two types of impulse wave used.

Voltages at the transformer were measured by means of a cathode ray oscillograph connected to a 1,070-ohm resistance potentiometer through a delay cable. Volt-

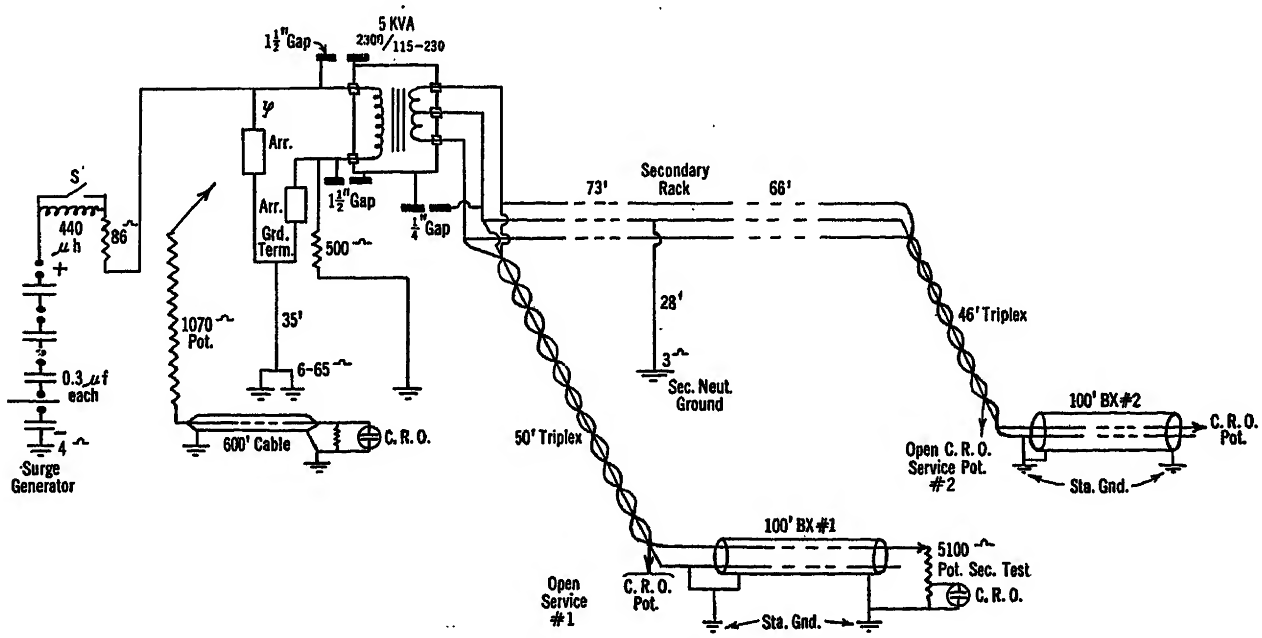

Fig. 6—Schematic Diagram of Test Circuit

TABLE I—CREST VOLTAGE MEASUREMENTS

Figure 7	Steep front surge				Slow front surge		
Column 1	2	3	4	5	6	7	8
	Standard connection		Arrester ground and sec. neutral interconnected	Arrester ground through secondary neutral only	Standard connection gaps not flashing	Arrester grounded through secondary neutral only	Arrester grounded through secondary arresters only Fig. 9A
Point of voltage measurement*	Gaps not flashing	Gaps flashing					
Arrester plus ground	+ 41 kv.	+ 50 kv.	+ 41 kv.	+ 62 kv.	+ 21 kv.	+ 21 kv.	+ 21 kv.
Arrester ground lead	+ 28	+ 36			+ 12		
Trans. sec. neutral		+ 20	+ 28	+ 43			
Open service No. 1	+ 3	+ 25	+ 20	+ 35	+ 3		
BX No. 1	− 3	+ 12	+ 16	+ 23	− 4	+ 8	+ 14
Open service No. 2	+ 3	+ 33	+ 34	+ 56	+ 4		
BX No. 2	− 3	+ 24	+ 18	+ 35	− 5	+ 10	+ 19
Oscillograms plotted	Fig. 8	Fig. 10	Fig. 11	Fig. 12	Fig. 9	Fig. 13	—

*All voltage measurements were made by resistance potentiometers

ages at the secondary service terminals were measured by a 5,100-ohm resistance potentiometer. These potentiometers of course have some effect on the surge voltages.

The Effect of the Ground Lead on Protection

To show the effect of inductance of the arrester ground lead on the voltage appearing across the primary bushing, two rates of current rise were selected. The slow rate of current rise was produced by introducing the 440-microhenry inductance into the circuit of the surge generator in Fig. 6. The steep front surge rose to a maximum of 1,200 amperes in two microseconds while the slow front surge rose to 900 amperes in nine microseconds. These are plotted in Fig. 7.

With the surge generator set to give a current wave of fast front and slightly less than 1,200 amperes crest, in order to prevent flashover of the transformer gaps, the oscillograms in Fig. 8 were taken. The maximum voltage across the ground lead and ground of the arrester was 28 kv. or about two times that across the arrester. This voltage fell to zero in two microseconds.*

The steady voltage across the secondary of about 3 kv. had a duration in the order of that of the current surge. These voltages across the two halves of the secondary differed in polarity. The voltage on the "open service" side of the winding was positive, the same polarity as the primary surge from line to ground.

In Fig. 9 are plotted the oscillograms obtained with the slow front surge under the above conditions of no gap flashovers and standard connections. The maximum voltage appearing from line to ground was 21 kv. The inductive drop in the ground lead plus the IR drop in the ground had a maximum value of 12 kv. The sum of the inductive and IR voltages in this case resulted in an approximately constant voltage up to maximum current. The secondary voltages were about 5 kv. and of long duration.

The two tests recorded in Figs. 8 and 9 indicate that after an initial disturbance determined by the surge impedance of the ground lead, the voltage across the ground lead is determined by the lead inductance and

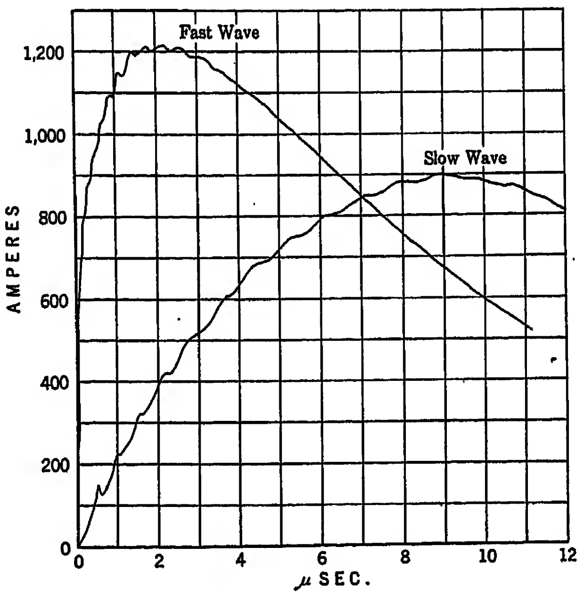

Fig. 7—Steep Front and Slow Front Current Surges Used for the Tests

the rate of change of current. The initial disburbance is due in part to the type of surge circuit used.

At the 1,200-amperes surge generator setting the transformer gaps flashed over at 50 kv. from line to ground. In Fig. 10 are plotted the voltage oscillograms obtained. The voltage across the arrester lead plus ground resistance was 36 kv., whereas the voltage across the arrester was only 15 kv. The oscillograms of voltage from case to ground and secondary neutral

*The gaps may have flashed accidentally during the oscillographic measurement of the voltage across the arrester lead plus ground, since the lack of sustained voltage as shown on the oscillogram seems incompatible with the given values of current and ground resistance, and also because the difference between the "arrester plus ground" and the "arrester lead plus ground" voltage is greater than the arrester voltage 15 kv. This curve is almost identical with the corresponding curve in Fig. 10.

to ground were almost identical so only one is reproduced. The voltage across the open service No. 2 was 33 kv. as compared to 24 kv. across *BX* No. 2, showing the reductive effect of the *BX* cable on the surge.

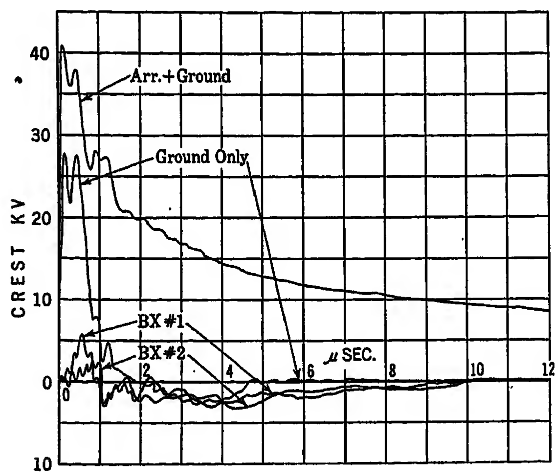

FIG. 8—VOLTAGES MEASURED IN CIRCUIT OF FIG. 6 WITH STEEP FRONT SURGE OF REDUCED MAGNITUDE
No transformer gap flashovers

INTERCONNECTION OF ARRESTER GROUND AND SECONDARY NEUTRAL

In Fig. 11 are plotted the corresponding voltages when the arrester ground terminal and secondary neutral are interconnected. No gap flashovers took

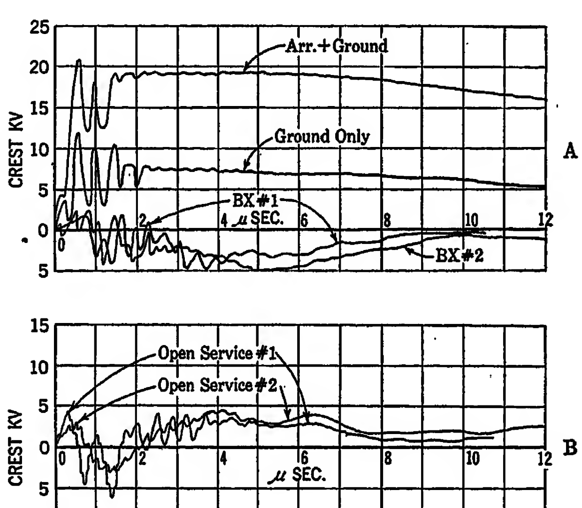

FIG. 9—VOLTAGE MEASURED IN CIRCUIT OF FIG. 6 WITH SLOW FRONT SURGE
No transformer gap flashovers

place. From Fig. 11 it can be seen that the difference in potential between the phase lead and the secondary neutral does not exceed 15 kv., the voltage permitted by the arrester alone.

A comparison of columns 3 and 4 of Table I indicates that the crest secondary voltages are about the same with the interconnection as they are during a flashover of the transformer gaps.

INTERCONNECTION AND A HIGH ARRESTER GROUND RESISTANCE

The extreme case of high ground resistance is that of having no arrester ground at all. Obviously the arrester cannot discharge and any surge above 50 kv. crest would flash over the transformer gaps. Protection under such conditions can be obtained by con-

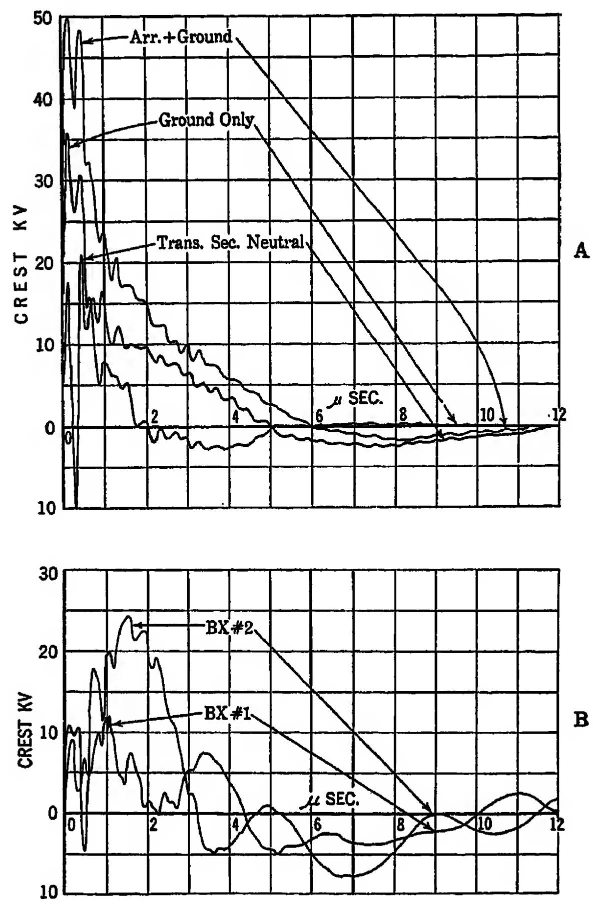

FIG. 10—VOLTAGES MEASURED IN CIRCUIT OF FIG. 6 WITH STEEP FRONT SURGE
Transformer gaps flashing over

necting the arrester ground terminal to the secondary neutral.

The circuit of Fig. 6 was modified by connecting the ground terminals of the primary arresters to the secondary neutral only. Under such conditions the full surge current flows to ground through the transformer secondary neutral wire. Figs. 12 and 13 show the voltages measured with the steep front surge and the slow front surge respectively. In neither case did the transformer gaps flash over, as the voltage across the transformer bushings was limited to about 15 kv. by the arrester. The maximum voltage to ground

with the fast surge was 60 kv. which was considerably above the gap flashover.

Indirect Interconnection of Secondary Neutral and Arrester Ground

The circuit shown in Fig. 5 was tested using the slow front surge but the separate arrester ground was omitted so that the only path for the arrester surge current was through the secondary arresters, secondary windings, and secondary neutral to ground. It is evident from a comparison of columns 7 and 8 of Table I that the leakage reactance between the two secondary windings of this transformer was high enough to increase the voltage appearing across the service wires.

This same circuit was tested with the steep front surge. The voltage was great enough to cause flashover of the *BX* cable so no measurement was made. No flashover of the transformer gaps occurred however.

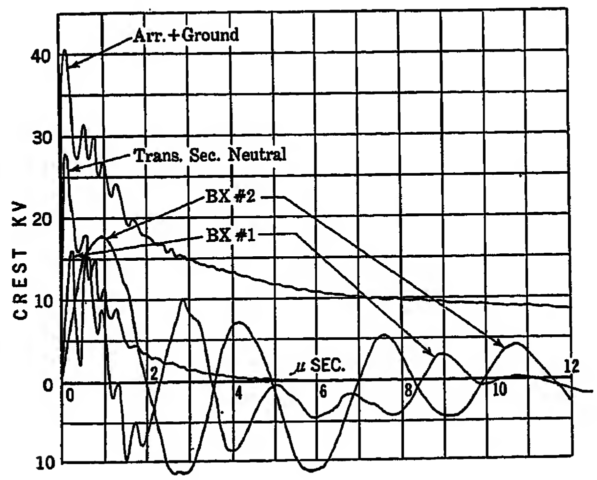

Fig. 11—Voltages Measured with Steep Front Surge in Circuit of Fig. 6 with Arrester Ground and Secondary Neutral Interconnected

No transformer gap flashovers

Surge Voltages Appearing on the Secondary

A surge voltage impressed across the primary of a distribution transformer will induce a voltage across the secondary. This voltage has a duration about the same as that of the primary voltage. A rapidly changing surge current passing to ground over the secondary neutral results in an oscillatory voltage appearing between the outside wires and ground at the service terminals. The maximum voltage is about the same as that of the transformer neutral to ground at the transformer. However, the voltage on the *BX* cable is lower than that on the corresponding open service. The voltage on the more distant service, No. 2, is greater than that on service No. 1.

The voltage appearing at the services when the arrester ground and secondary neutral are interconnected is about the same as that appearing when a steep front surge causes the transformer gaps to flash over due to inductive drop in the arrester ground lead.

The secondary voltages with the arrester ground and secondary neutral interconnected, though of short duration, appear to have a rather high magnitude. While the secondary voltages with this circuit may be compared with the secondary voltages on the other

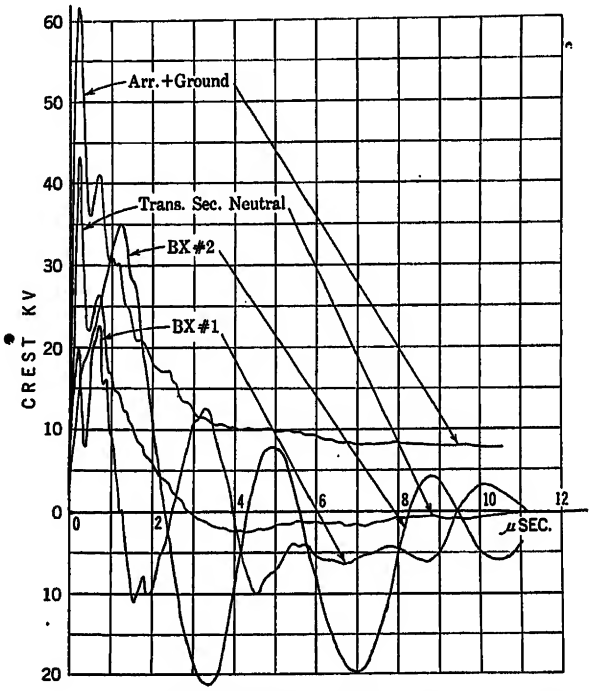

Fig. 12—Voltages Measured with Steep Front Surge in Circuit of Fig. 6 with Arrester Ground Removed and Arrester Connected to Secondary Neutral Only

No transformer gap flashovers

circuits tested, it should be noted that the length of racked secondary was short compared to lengths usually occurring in practise, and that actual voltages will probably be lower. Voltages of the relative magnitude tabulated in column 3 of Table I appear

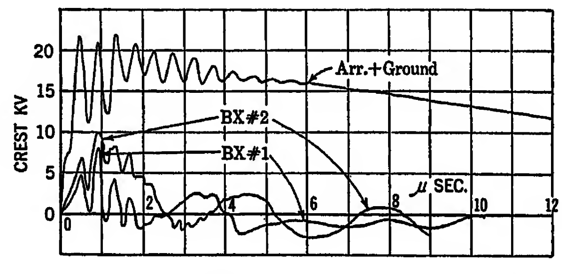

Fig. 13—Voltages Measured with Slow Front Surge in Circuit of Fig. 6 with Arrester Ground Removed and Arrester Connected to Secondary Neutral Only

No transformer gap flashovers

now without serious effect, in the case of transformer flashovers where the ground resistance is low.

Conclusions

Under present methods of distribution transformer protection, flashovers of bushings or windings due to

lightning often occur, causing dynamic current flow into the secondary circuit with resultant transformer outages. Tests show that, when a transformer is subjected to a lightning surge, the case will assume a potential of about 10 per cent of that appearing between the primary leads and secondary neutral. Neglecting the potential on the case, the voltage across the transformer bushings is the sum of the voltages across the arrester, the arrester ground lead and the arrester ground resistance. With a steep front surge, the inductive voltage across the ground lead alone may exceed the arrester voltage. Remedial steps which can be taken are limited to a reduction of the arrester ground resistance and of the inductive drop across the ground lead. Practical application of these measures is limited by available field conditions.

Improved protection of the transformer may be secured by any one of several methods of connecting the arrester ground lead to the secondary circuit. The following methods will limit the surge voltage across the bushings to approximately the characteristic crest voltage of the primary arrester, but will differ in resulting secondary voltages.

1. Direct connection of a low resistance primary arrester ground to a grounded secondary neutral produces no higher voltages at the customer's service than are experienced when flashover occurs with the present protection schemes.

Direct connection of a very high resistance primary arrester ground to a grounded secondary neutral results in higher surge voltages appearing on the customer's leads than when the ground resistance is low.

2. Connection of the primary arrester ground to the secondary neutral through a low-voltage arrester gives substantially the same results as with the direct connection.

3. Connection of the primary arrester ground to the secondary outside wires through two low voltage arresters, results in increased customer voltage.

The authors wish to express their appreciation to E. R. Whitehead for his valuable assistance with these tests.

Discussion

For discussion of this paper see page 271.

Studies in Lightning Protection on 4,000-Volt Circuits—III

BY D. W. ROPER*

Fellow, A.I.E.E.

Synopsis.—The advancement in knowledge of lightning protection, as developed by the investigations in Chicago since the 1920 paper on the same subject, has been largely due to an intensive study in the past five years made with the active cooperation and assistance of the manufacturers of lightning arresters. The development in recent years of methods of laboratory tests with the lightning generator and the cathode ray oscillograph render unnecessary a continuance of these statistical research investigations.

The examination of 474 transformers burned out by lightning indicates the desirability of line transformers with non-aging insulation which will be lightning-proof against induced discharges when protected by the modern types of arresters. A comparison of the troubles on the distribution system due to lightning in Chicago with similar results in other cities indicates that considerable advantage is obtained by the use of the four-wire three-phase system with grounded neutral. Induced discharges of 400 kv. crest value have been noted. Direct strokes account for only 5 per cent of transformer troubles. No evidence could be found of shielding effect against induced discharges due to adjacent high trees, buildings, or other structures. Traveling waves are not a factor in the transformer troubles on the distribution system in Chicago. Modern types of lightning arresters excel the best type of 20 years ago in reduced annual charges, but not in efficiency as a protective device. Extra expense to reduce resistance of lightning arrester grounds below 50 ohms is not warranted.

By following the principles developed during these investigations and using transformers of improved design, it appears possible to effect a reduction in Chicago in the rate of transformer troubles due to lightning from 13 cases to 1 case per 1,000 transformers per year.

* * * * *

INTRODUCTION

THIS paper presents the later results of a statistical research investigation that has been in progress for over 20 years. (Fig. 1.)

About the time of the presentation of the 1920 paper[1] on this subject, the manufacturers of lightning arresters were consulted regarding the advisability of discontinuing the investigations on account of the expense. They were opposed to any such plan, as the statistical method described in that paper was the best method then available of securing information regarding the relative protective value of the different types of arresters. It was, therefore, decided to continue the studies, and it was also arranged to install in moderate quantities, for trial purposes, several new types of arresters then being developed.

The lightning machine was developed about 1921 as a device for testing arresters, but the spark gap was the only measuring instrument then available for making comparative observations. About 1924 the cathode ray oscillograph and the necessary accessories were developed in form suitable for use as a measuring instrument[2] on tests made with the lightning machine. In 1926 it was noted that the results of such tests, as then made and interpreted, placed the several types of arresters then on the market in a different order of merit from the order indicated by the field investigations in Chicago. This resulted in a 5-day conference with the manufacturers in January, 1927, to discuss these differences and devise plans for further procedure. As it appeared at this conference that the discussions would be greatly facilitated if the results obtained on all types of arresters could be exposed in the conference to all of the manufacturers, their representatives agreed to this procedure and further agreed that they would not use the information to the disadvantage of any competitor. This agreement was the greatest forward step taken

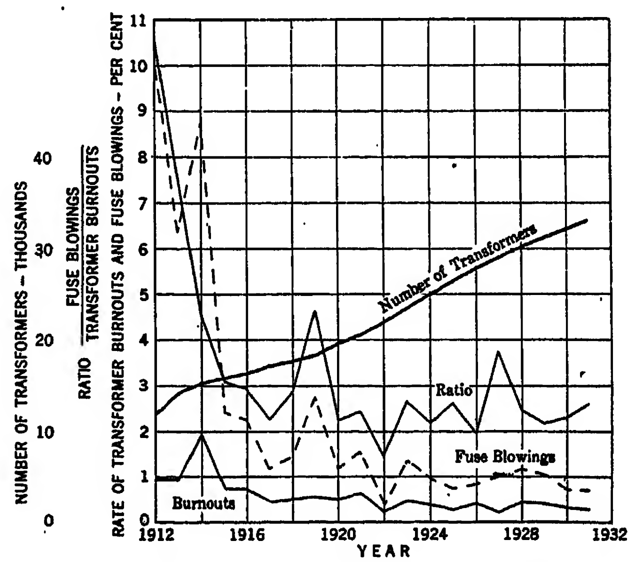

FIG. 1—RECORDS ON TRANSFORMERS AND LIGHTNING TROUBLES FOR 20-YEAR PERIODS

Even though the number of transformers doubled between 1915 and 1931, the actual number of transformer burnouts and fuse blowings remained fairly constant during the period at 105 and 275 per year respectively

in connection with these investigations. Most of the increased knowledge obtained by the investigations in Chicago since the 1920 paper has resulted from the intensive study begun during this conference and continued in the five succeeding years.

About 25 factors which might affect lightning ar-

*Superintendent, Street Dept., Commonwealth Edison Co., Chicago, Illinois.

1. For references see Bibliography.

Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 25-29, 1932.

32-19

rester performance or transformer troubles caused by lightning were listed. An investigation, made for each of 119 locations where transformers had failed during the previous year, showed that about one-third of the factors first listed occurred so infrequently that they were of no serious consequence and were quickly dismissed from further investigation.

Additional information regarding the factors which appeared important was sent to the manufacturers and discussed in six later conferences. As a result of this procedure, and by utilizing the results of the laboratory tests and field investigations made by the manufacturers during these years, all differences of opinion that were noted in 1926 have been reconciled. The manufacturers have been of invaluable assistance in reaching practically all of the principal conclusions in this paper, and they are now able to make tests with the lightning generator and interpret the results shown by the cathode ray oscillograph, so that the relative merits of various types of lightning arresters can be very closely determined by laboratory tests. The expense of the statistical research investigations in Chicago is, therefore, no longer warranted and it has been materially reduced.

It would be very interesting indeed if the manufacturers could arrange to publish, side by side, the test results and analyses of studies made with the lightning generator and the cathode ray oscillograph on several radically different types of arresters, so as to show how the relative protective value of arresters can be determined.

Description of System

The system of distribution used in Chicago is a four-wire three-phase 2,300/4,000-volt system with the neutral connected to ground through a reactor shunted by a fuse in each of the 57 substations. All of the 606 circuits leave the substations via underground cables, the feeders are entirely underground, and about 20 per cent of the primary mains are also underground. There were 33,093 transformers on August 1, 1931, connected to the overhead mains and in addition 1,593 were installed in manholes or vaults and connected directly to underground primary mains. Over 800,000 customers are served by this system of distribution.

All line transformers are single-phase, with 2,080-volt primary and 115/230-volt secondaries. Lighting transformers are connected between one primary phase wire and the primary neutral; the neutral wire of the secondary is usually grounded on the pole next adjacent to the transformer and if the secondary main is more than one span long the neutral is grounded at two poles. Transformer cases are not grounded. Small lighting customers have two-wire services, but all large lighting customers have three-wire services, and in either case the neutral is grounded to a water pipe on the customer's premises. Secondary lighting mains are generally only one block long. Installations for three-phase power customers consist of three transformers connected in *Y* on the primary and in delta on the secondary. The common point of the transformer primary connections is *not* connected to the primary neutral; the middle point of one transformer secondary is grounded. For the smaller power customers, two transformers are used, each connected between one phase wire and primary neutral with the secondaries in open delta. About 55 per cent of all transformers are single transformer lighting installations, 15 per cent are in 2-transformer banks supplying both light and power, and 30 per cent are in 3-transformer 3-phase banks supplying power only.

About two years ago the plan was adopted of interconnecting the neutrals of all secondary mains wherever this could be done at reasonable expense, and about 80 per cent of these connections have been completed.

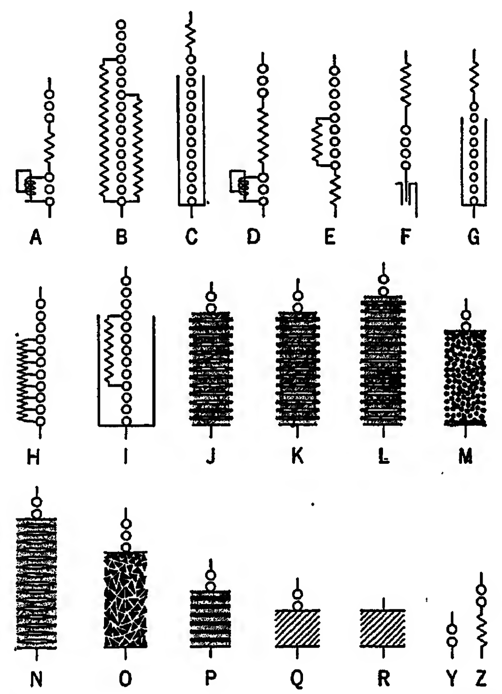

Fig. 2—Electrical Diagrams of Arresters Used

The gaps and resistors are conventional. Lower end of diagram is ground side. Types *A* to *R* are 3,000-volt arresters. Types *Y* and *Z* are 300-volt arresters. In types *C* and *G* narrow grounded bands of metal are carried up the sides, while in type *I*, a grounded metallic cylinder surrounds the lower three-quarters of the arrester. Arresters *J* to *R* are valve types. Arresters are arranged in the order they were installed on the system

On 80 per cent of the circuits, the maximum distance between transformers is less than 1,000 ft. measured along primary mains. At about 370 locations the primary mains are without transformers for distances greater than 1,000 ft.; and at 25 locations, greater than 2,000 ft.

Many of the larger transformers are so located that there is no secondary wire exposed to induced lightning discharges.

The City of Chicago covers about 210 square miles. Eliminating areas in which no overhead lines are installed, the system covers about 120 square miles. The system includes about 135,000 poles, of which about 3,800 are cable poles.

One 3-kv. and one 300-volt arrester (Fig. 2) are installed on the same pole with each lighting transformer, while on 3-transformer installations there are three 3-kv. arresters and one 300-volt arrester, with the further limitation that the maximum number of arresters in any one block is three 3-kv. and one 300-volt arrester. Similar installations of arresters are made on all cable poles and arresters are omitted from transformers within 300 ft. of these poles. There are no lightning arresters or similar devices in any of the substations or on the secondary mains for light or power, and no lightning arresters are installed on transformers connected to underground mains. There are no fuses on the secondary wires outside of customers' premises.

There are now 15 types of 3-kv. arresters on the system, which, for the purpose of this investigation, was divided into 162 areas. Only one type of lightning arrester was installed in each area. The several areas for each type of arrester are scattered throughout the city and in regions of varying arrester density, in an attempt to put all types of arresters on the same basis. Separate performance records have been kept each year for each of these segregated areas.

TABLE I—RESULTS OF EXAMINATION OF TRANSFORMERS BURNED OUT BY LIGHTNING
AVERAGE DATA FOR 1927–1930, INCLUSIVE

Apparent Lightning Entrance	No.	Per cent
Primary only		
Phase wire	133	28.0
Neutral wire	32	6.8
Phase and neutral wire	42	8.9
Total, primary only	207	43.7
Secondary only	100	21.1
Secondary and primary	105	22.2
Doubtful	38	8.0
Indeterminate	24	5.0
Total	474	100.0

Note: In these investigations a transformer is considered to be burned out when it cannot be restored to service without removing it from the pole. About 40 per cent of the transformers were repaired without replacing the coils.

The terrain in Chicago is quite flat as, with one minor exception, the maximum difference in elevation as shown by the Geological Survey maps is less than 50 ft. Satisfactory grounds can usually be secured in most of this area by 10-ft. ground rods except along certain sand ridges where 15-ft. ground rods are used. In a few localities of quite limited area, the rock is within a few feet of the surface, and special methods are used to secure good lightning arrester grounds.

Examination of Burned Out Transformers

The records of the examination of 474 transformers burned out by lightning (Table I) indicate that burnouts which start on the secondary winding (Fig. 3) were nearly one-half of those starting on the primary. This information led to a discussion of the desirability of installing lightning arresters on the secondary mains. Arrangements were made to have this subject investigated at Purdue University, and some of the results of that study are reported in a separate paper.[3]

During the examination of these transformers, considerable information was obtained which confirmed a suggestion in the 1914 paper[4] of the author, reading as follows:

> It is suggested that careful attention by the manufacturers to the primary bushings, the clearance of the primary leads inside the case, the manner of their support, and other minor details, would probably result in a material improvement in these records.

Many bushings, especially in the older transformers, were so small that they were apparently designed to withstand the operating voltage rather than the transient voltages to which they would be subjected when installed on overhead pole lines.

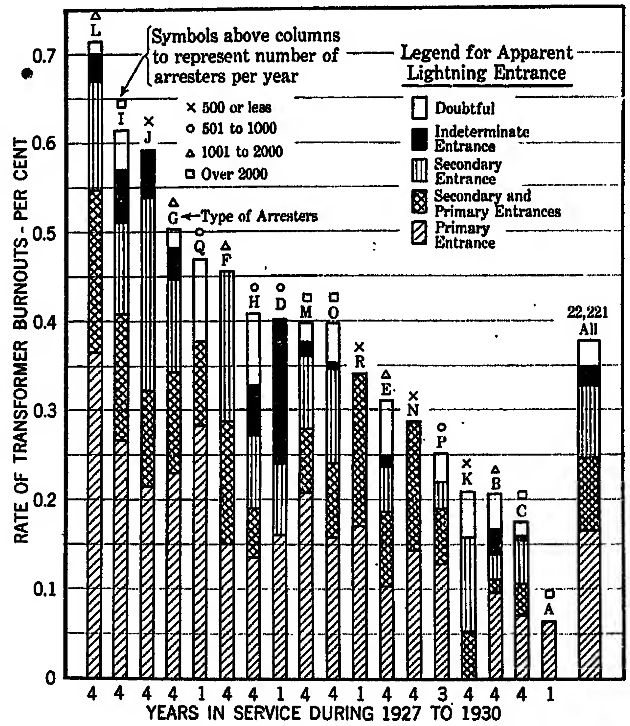

FIG. 3—LIGHTNING ARRESTER PERFORMANCE

The averages are not corrected for size, age, and density of transformers. Probable errors in the individual cases are from 10 to 25 per cent, except for type *A*, for which only one year's performance is shown.

Burnouts are subdivided according to apparent path of entrance of lightning as indicated by examination, and extent of primary and secondary wires is considered

If induced discharges on overhead secondary mains are the cause of transformer burnouts by lightning, it appeared possible that some damage might occur to customers' equipment. A search of the records for three calendar years of the departments that would be involved showed that the total cost of all repairs to customers' wiring, or replacement of lamps or household equipment or devices, averaged less than $100 per year. About 40 failures of watt-hour meters per year appear to be due to lightning.

Induced Discharges, Direct Strokes, and Traveling Waves

There is no general accord as to what evidence is considered a conclusive indication of a direct stroke, but if only those cases are included in which there is some shattering of poles or cross-arms, or severe external burning of transformer cases or other equipment on poles, or damage to trees immediately adjacent to the primary wires, then evidence is found of direct strokes on only about 15 poles per year, or about 1 in 9,000. About 5 per cent of the transformer failures due to lightning appear to be caused by direct strokes, and so the other 95 per cent must be due to induced discharges.

Two well defined cases have occurred where, with the assistance of the manufacturers, it was determined that a maximum transient voltage of the order of 400 kv. was indicated. In each instance the maximum dimension across the area, in which signs of damage could be discovered, was less than 1,500 ft.

A large fraction of the transformers on the system are installed at the ends of primary mains remote from the feeding point, and if there are traveling waves on the distribution system, the transformers installed at these open ends should show an increased percentage of failures or fuse blowings due to the piling up of the voltage at such open ends. The records for transformers at such locations show that the percentage of trouble is about 20 per cent below the rate for other transformers on the system. (Table II.) It appears that, as the distance

TABLE II—EFFECT OF TRAVELING WAVES IN CAUSING BURNOUTS OF TRANSFORMERS IN 1931

	Per cent
Ratio of transformers installed within 100 ft. of open ends of primaries to system total	.46
Ratio of burnouts on these transformers, due to lightning, to total on system	.41
Ratio of rate of burnouts on transformers near open ends of primary mains to rate for all others	.82

between arresters is generally below 1,000 ft., transient voltage waves can not travel very far before they are dissipated through the lightning arresters and rendered harmless.

Underground Primary Mains

The records of transformer troubles due to lightning, presented in this paper, do not include 1,593 transformers which are installed in manholes or vaults. A separate record of these transformers shows only two failures in the past five years due to lightning, or about 1/30 of 1 per cent per annum.

Effect of Various Factors on Lightning Troubles

Grounding the Primary Neutral. One advantage of a four-wire three-phase system with the neutral grounded in the substation is that it permits the installation of 300-volt arresters on the neutral wire of the overhead primary mains and 3-kv. arresters on the primary phase wires, whereas, with the neutral ungrounded, arresters rated at 3 kv. and 6 kv. are required. The neutral arresters, consisting of a single gap between metal electrodes, sometimes with a low resistance in series, will spark across below 3 kv.; therefore, as the transient voltage rises, these neutral arresters will spark across in about 1/5 of the time required for the transient wave to reach a voltage at which the phase arresters will discharge. If, during induced lightning discharges, the primary neutral wire were grounded at the substations, only, it would not be a factor in reducing troubles caused by lightning; but as a result of this action of the arresters on the primary neutral wire, that wire becomes grounded at each neutral arrester; and it then serves just as efficiently as a ground wire to reduce the maximum voltage, which would otherwise be reached by the primary phase wires, as a special ground wire installed for the purpose. This factor, together with the use of phase-wire arresters of lower voltage rating, gives the grounded neutral system an advantage over systems with ungrounded neutral of a reduction of about 40 per cent in the maximum crest voltage to which the transformers are exposed by induced discharges and this advantage cannot be overcome by the use of any special schemes or devices applicable to the ungrounded system.

As a result of these reduced transient voltages, and in spite of the fact that no lightning arresters are installed in the substations, flashovers due to lightning on the buses or connections in the distribution substations in Chicago are entirely unknown, and the burnouts of voltage regulators due to lightning in recent years have averaged about 1/20 of 1 per cent per annum. In contrast with this situation, may be cited the experience with an ungrounded neutral system having an operating voltage about 25 per cent higher than in Chicago, where the flashovers in the substation had become so serious that a special research investigation[5] was undertaken to determine the cause and the remedy.

A further indication along the same lines is found in the insignificant number of cable failures due to lightning, *viz.*, about 2 per year with 3,800 points of connection between the underground cables and overhead primaries.

Density of Arresters. This subject, quite thoroughly covered in the 1920 paper,[1] is one of the most important factors. Similar calculations, repeated for several succeeding years, confirm the results given in that paper.

Size of Transformers. Recent records confirm the statements and figures in the preceding papers that the percentage of troubles decreases with increasing size of transformers. In Chicago some reduction of troubles has been secured by discontinuing purchases of transformers below 5 kva. capacity.

Age of Transformers. Only 7 per cent of transformer burnouts due to lightning have occurred on transformers less than 5 years old, (Fig. 4) over 75 per cent

occurred on transformers more than 10 years old, and the per cent of failures increases with their age.

Resistance of Lightning Arrester and Secondary Neutral Grounds. The records in recent years show no significant change from the results reported in the 1920 paper. The records apparently indicate, however, that any extra expense to reduce the resistance of lightning arrester grounds below 50 ohms is not warranted.

Shielding Effect of Trees, Buildings, Etc. Considerable time and effort has been expended in an attempt to determine to what extent, if any, lightning troubles are reduced by the shielding effect of trees and structures adjacent to the overhead lines. As near as could be determined by the methods used in this investigation, this shielding effect is practically zero. Numerous instances have been noted where transformers in such locations failed during lightning storms. Theoretical considerations do not indicate that any protection should be expected from such structures, as long as 95 per cent of the troubles are due to induced discharges.

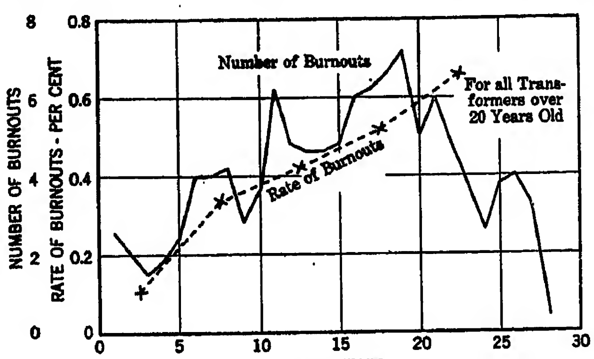

FIG. 4—RELATION OF AGE OF TRANSFORMERS AND BURNOUTS DUE TO LIGHTNING

Figures shown are averages for 1927 to 1931

ACCURACY OF RESULTS

In making research investigations on a subject in which there is a number of variables, it is recognized that, in order to determine the effect of any one variable, all others must be held constant. This, of course, is obviously impossible in field investigations of lightning protection. In spite of all attempts to eliminate the lightning as a variable, the relative performance (Fig. 5) of different types of arresters varies widely from year to year, indicating that the lightning still remains the dominant variable. It seems reasonable to assume that the average results obtained with the different types of arresters over a period of years (Fig. 5) may be in error in individual cases by an amount ranging from 10 per cent to 25 per cent of the values shown. For example, experience in preparation of the 1920 paper[1] shows that the relative order of merit of the different arresters, as shown in Fig. 3, would be altered if density of arresters were taken into consideration.

COMPARISON OF DIFFERENT TYPES OF ARRESTERS

A careful examination of the records obtained from various types of lightning arresters shows that one of the types (*B*, Fig. 3) first placed on the market about 20 years ago and withdrawn about 10 years later, has not been excelled in its protective efficiency by any later arrester. It consisted of a series of metal gaps with two shunting resistors enclosed in a wooden box. This arrester, in common with others of that period, had the disadvantage of requiring annual inspection and maintenance with occasional replacements of some of the parts or the enclosing wooden box or, at times, replacement of the entire arrester. Severe discharges would occasionally melt the metal cylinders and bridge the gaps, so that the arrester would not withstand the application of the working voltage across its terminals and, therefore, it interrupted the service on that circuit until

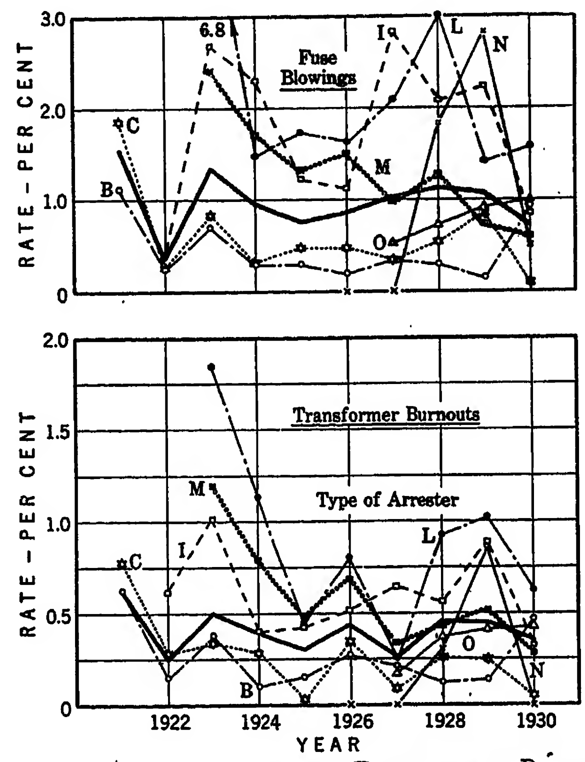

FIG. 5—RECORDS OF TROUBLE ON TRANSFORMERS PROTECTED BY TYPICAL ARRESTERS

Heavy solid line represents average for all arresters on the system

the arrester could be located and disconnected. The manufacturers recognized that lightning protection is an economic problem, and the next step was to produce arresters of the discharge gap type, but enclosed in a porcelain tube instead of a wooden box, so that the annual inspection was eliminated. They still retained in some degree, however, the other defects of type *B*.

The first arrester of the so-called "valve type" was installed on the Chicago system in 1922. Since that time, all new types of arresters placed on the market by the three principal American manufacturers have been of the valve type. The replacements of the valve type required by failures in service are about one-third of similar replacements of the gap type arresters enclosed in porcelain. The ideal valve type arrester is one without a series gap that will discriminate between induced

discharges of high frequency and the 60-cycle follow current, opening wide the valve for the former and closing it promptly against the latter, and repeat the action year after year without reduction in its protective efficiency. Considerable progress has been made in these designs in reducing the annual maintenance and the replacements, and it appears reasonable to expect that a valve type arrester will shortly be produced having a protective efficiency equal to type *B*. One type of arrester, type *M*, appears to improve in efficiency with age as indicated by the records in Fig. 5.

Coordination of Equipment

In recent years there have been presented to the A.I.E.E. several papers on the subject of coordination of insulation on transmission lines. Apparently the same general principle can be extended to distribution circuits under the term "coordination of equipment," that is, coordination between the performance of protective devices and the equipment which they protect. In this case it means a coordination between lightning arrester performance and the transient voltage limit of distribution transformer windings and bushings. For example, if 50 kv. is the upper limit of the transient voltage between the line terminal of a lightning arrester and ground at the time of induced lightning discharges, then the transformer, when tested by the application of the proposed A.I.E.E. standard impulse waves, should withstand a transient voltage test of at least 100 kv. in order to secure reasonable immunity from lightning troubles. This means that there should be some coordination between the work of the A.I.E.E. Committee on Lightning Arrester Standards and the Committee determining standard tests for distribution transformers. It appears possible to design and construct, at reasonable cost, distribution transformers that will be practically immune to lightning troubles when protected by the modern types of lightning arresters.

Suggestions for Securing Minimum Lightning Troubles on Distribution Circuits

1. Use the four-wire three-phase system of distribution with grounded neutral.

2. Where transformers or cables are connected to overhead primary mains, install low-voltage arresters on the neutral wire and valve type arresters suitable for the *Y* voltage on the phase wires; avoid duplication within 500 ft., and reduce the number, for Chicago conditions, by one-third.

3. Use transformers having insulation on the coils and leads that will not deteriorate with age and which will withstand a transient voltage test safely above the voltages to which the transformer will be subjected in service when protected by the arresters.

4. If conditions warrant a second ground rod for reducing the resistance of the lightning arrester ground, install also a second ground wire down the pole and connect it to the second ground rod.

5. Select newest transformers for installation in districts of low arrester density and install the older transformers in high density areas.

6. Require each customer to ground the neutral wire of his house wiring to a water pipe on his premises.

7. Connect the neutral wire of each section of secondary mains to at least two ground rods; on long mains install ground rod connections at intervals not exceeding 600 ft.

8. Interconnect, to a reasonable extent, the neutral wires of adjacent secondary mains.

9. Interconnect the lightning arrester ground wire and the secondary neutral wire when the latter is well grounded.

10. Where transformers are connected to primary mains 1,500 ft. or more distant from the nearest transformers, install on the pole about 600 ft. from the transformers the same lightning arrester equipment as on the transformer pole.

11. Ground the lead sheaths of all underground primary cables.

By following these suggestions and giving the subject continuous engineering supervision, it appears possible to reduce the number of transformer troubles in Chicago caused by lightning, that is fuses blown plus transformers burned out, to less than one case of trouble per year per one thousand transformers installed.

It is regretted that the limitations of space do not permit the presentation of all the data on which the conclusions and suggestions in this paper were based.

Acknowledgment

The author gratefully acknowledges his indebtedness to those of his own staff and the engineering and testing departments who have contributed to these investigations, and especially to H. Halperin who has had general charge of the studies in recent years and materially assisted in the preparation of the paper, and R. R. Schump who has compiled most of the records and prepared the voluminous reports to the manufacturers.

The author is also indebted to V. E. Goodwin and K. B. McEachron of General Electric Company, J. R. McFarlin of Electric Service Supplies Company, and A. L. Atherton and E. Beck of Westinghouse Electric and Manufacturing Company for their careful study of the reports of field observations and their generosity in furnishing results of their laboratory tests, many of them unpublished, during the course of the investigations, and especially for their broadminded policy in setting aside commercial rivalry during seven different conferences lasting seventeen days, so that the investiations might be most efficiently conducted.

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Discussion

For discussion of this paper see page 271.

Lightning Protection for Distribution Transformers

BY T. H. HAINES* and C. A. CORNEY*
Member, A.I.E.E. Member, A.I.E.E.

Synopsis.—This paper presents a five year history of the results of lightning arrester protection for distribution transformers in New England where the normal ground electrode resistance is much higher than in most other parts of this country.

The experience shows that the trouble rate of the protected transformers has consistently been materially less than that of those not protected, notwithstanding the seemingly adverse conditions. It also shows that the effectiveness of the arresters is practically independent of the ground resistance when above a value of 100 ohms.

Design features of transformers are shown to be of prime importance in reducing flashovers in and around the equipment.

* * * * *

Description of System

THE Edison Electric Illuminating Company of Boston distributes electrical energy in 40 cities and towns, embracing 650 square miles in and about the city of Boston. The soil is generally sandy and rocky and of such a nature that the obtaining of what are generally considered low resistance grounds is extremely difficult if not impossible. There are many hills and valleys and numerous rivers and small streams wind through the territory. A total of 325,000 retail customers is supplied from 10,200 distribution transformers. All power customers are fed from three-phase transformers of which there are 1,500 overhead and 500 underground. Of the single-phase lighting transformers, 7,300 are overhead and 900 underground.

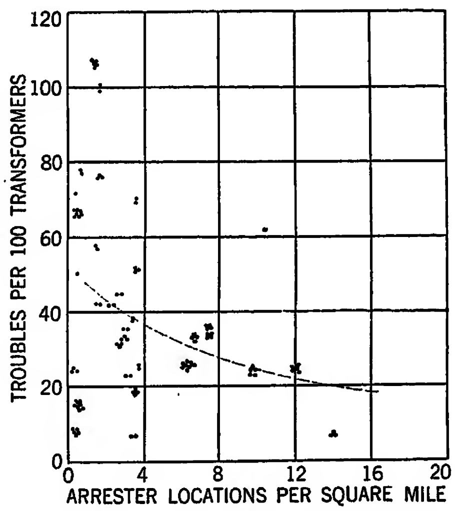

Fig. 1—Variation of Trouble Rate with Lightning Arrester Density 1927

Note: Individual points or groups of points represent the observations in a single town; the number of points in any group being approximately proportional to the number of transformers in the town

In general, the primary distribution system is radial in type and operates at 2,300/4,000 volts, three-phase, four-wire, with the neutral ungrounded. There are approximately 235 such circuits of which 20 per cent of the circuit miles are estimated to be underground.

Introduction

This investigation was undertaken to determine, if possible, a means of lessening or eliminating the troubles in and about distribution transformers due to lightning.

For years, the occurrence of lightning storms in this territory has been accompanied by numerous blown fuses, damaged and burned out transformers, and other troubles, all of which caused considerable outage to customers with consequent annoyance to them as well as expense to the Company.

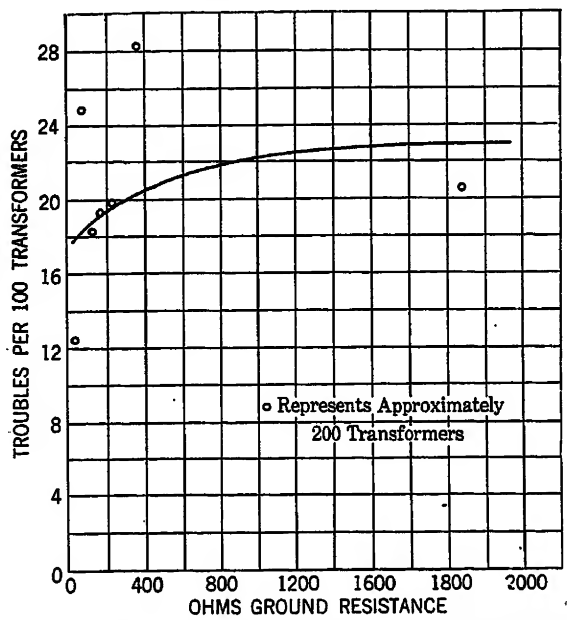

Fig. 2—Variation of Trouble Rate with Ground Resistance 1927

Lightning arresters of conventional type had not been used to any extent principally due to the opinion that in order to have satisfactory performance of this equipment it was absolutely essential to have low resistance ground connections. Those familiar with New England soil conditions realize that a low resistance ground at the foot of a pole is a rarity. This condition was empha-

*Both of the Edison Electric Illuminating Company of Boston.

Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 25-29, 1932.

sized in 1917 when the Bureau of Standards made a general survey of ground resistance conditions and found that they were worse in New England than anywhere else in the country.[1]

Preliminary Study

With the growth of the system conditions were becoming so acute that early in 1923 it was decided to make a trial installation of a number of standard lightning arresters notwithstanding the fact that there was little hope of getting what was considered a low resistance ground. It was at first necessary to determine where and how a start should be made.

Trouble records as related to the effects of lightning were rather meager at that time, but there were available records of the locations of all transformers which had been changed on account of lightning troubles for a period of years previous to 1923. These locations were spotted on a map of the system, and some of the circuits in the areas where the spots were thickest were chosen as the first to be protected.

From past experience certain areas in and closely adjacent to the City of Boston had shown a trouble rate about one-third that of the rest of the territory, and usually much under 10 per cent. There is now a total of 3,400 overhead transformers in these areas, none of which is protected by lightning arresters. As this section is more thickly settled than the rest, its comparatively low rate is thought to be due to the shielding effect of structures. As a result of the above, no protection was intended for this area and it has consequently been eliminated from the study. Fig. 3 shows the protected area in which there are now approximately 5,400 overhead transformers.

Procedure

Lightning arresters rated for circuits of 4,000 to 5,000 volts, of three manufacturers each having seemingly desirable characteristics and porcelain housings, were selected. Single-phase transformers which are connected between a phase wire and neutral were equipped with two arresters, one from each wire to ground. Three-phase transformers which are connected to each of the three-phase wires were similarly equipped with three arresters. It was planned to equip about 500 locations a year.

As it was estimated to cost an average of $50 per transformer for lightning arrester protection, it was not deemed economically justifiable, in general, to install the equipment on transformers under 7.5 kva. capacity. As the records showed, however, that transformers on dead ends were more susceptible to lightning troubles than the others, it was decided to protect those as small as 5 kva. capacity at these locations.

Due to the previously mentioned opinion as to the necessity for low resistance grounds, it was decided that, for the first trial group, lightning arresters would not be installed unless a ground connection of 250 ohms or less could be obtained. Even this value of ground resistance will appear unreasonably high to many who are accustomed to readily obtaining values as low as one-tenth of this figure or even less.

Accordingly in 1925 the first group of arresters was installed. It was soon found after work had started that even 250-ohm grounds were difficult to obtain and consequently, in order to be able to complete a reasonable number of installations for observation, the limit above which arresters should not be used was raised to 1,000 ohms.

1927 Study

No attempt was made to analyze operating records until 1927 as it was thought that the number of installations in service previous to that time was too small to obtain reliable data. The operating forces were kept acquainted with the progress of installations and the object and aims of the proposed study, and were impressed with the desirability of complete and accurate records of troubles.

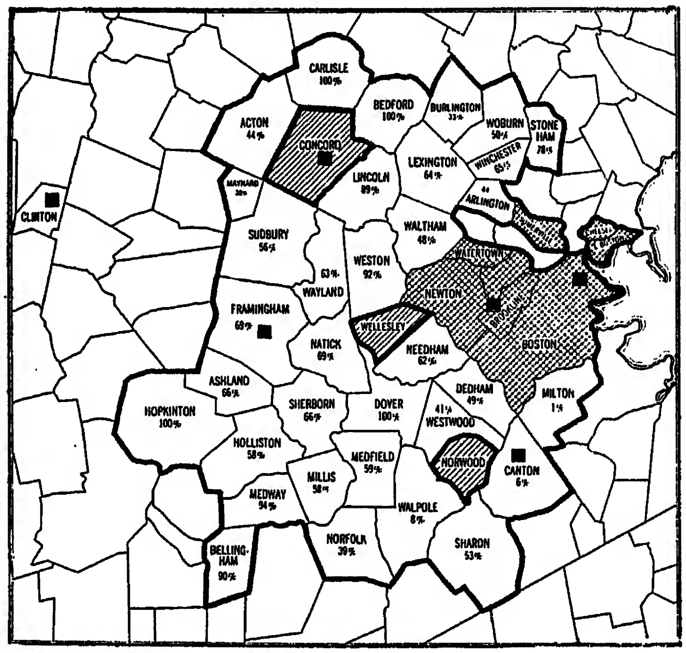

Fig. 3—Map of the System

1. Protected and unprotected areas
2. Per cent protection in each town 1930
3. Locations of the Weather Bureau observation stations
Edison territory is shown within heavy line
Single crosshatched areas have municipal distribution
White areas indicate ultimate 100 per cent arrester protection
Double crosshatching indicates unprotected area
Black squares indicate observation stations of the U.S. Weather Bureau
Acton and Maynard were added to the system in 1929

From the procedure established, it will be noted that in any area selected for protection some transformers were protected and some were not. It was thought that in general this practise would give us a means of com-

1. Bureau of Standards publication No. 108, "Ground Connections for Electrical Systems," by O. S. Peters, dated June, 1918.

TABLE I—PER CENT TRANSFORMER TROUBLES DUE TO LIGHTNING, 1927

Protected area towns grouped according to % L.A. protection	% Protection	Av. Ground resistance	Transformers with L.A.'s troubles per 100 trans.: No. trans. with L.A.'s	Fuses blown	Defects in windings	Miscellaneous defects	Total No. troubles per 100	Transformers without L.A.'s troubles per 100 trans.: No. trans. without L.A.'s	Fuses blown	Defects in windings	Miscellaneous defects	Total No. troubles per 100	All transformers: Total trans.	Troubles in year	Troubles per 100 trans.
1. Ashland	63	167	47	6.4	0.0	10.7	17.1	28	21.4	0.0	25.1	46.5	75	19	25.4
2. Bedford	64	141	45	22.2	0.0	15.6	37.8	25	32.0	0.0	12.0	40.0	70	27	38.6
3. Neeham	73	403	150	3.3	.7	5.3	9.3	54	33.3	0.0	14.8	48.1	204	40	23.5
4. Stoneham	78	129	86	2.3	0.0	0.0	2.3	24	19.2	0.0	3.8	23.0	110	8	7.3
5. Sudbury	64	49	65	7.7	0.0	26.1	33.8	36	13.9	0.0	13.9	27.8	101	32	31.7
6. Weston	74	360	128	13.3	0.0	16.4	29.7	45	42.2	2.2	13.3	57.7	173	64	35.2
Group 60-80		259	521	8.1	0.2	11.1	19.4	212	28.8	0.5	12.7	42.0	733	190	25.9
7. Burlington	42	174	25	12.0	0.0	8.0	20.0	35	34.3	0.0	22.8	57.1	60	25	41.7
8. Dover	52	183	55	40.0	1.8	21.8	63.6	51	29.4	0.0	11.7	41.1	106	54	51.8
9. Holliston	59	166	50	14.0	0.0	26.0	40.0	35	31.4	0.0	17.0	48.4	85	37	43.5
10. Hopkinton	59	128	44	68.2	0.0	15.9	84.1	31	93.5	0.0	38.7	132.2	75	75	100.0
11. Medfield	50	173	44	9.1	0.0	13.7	22.8	43	18.6	0.0	4.6	23.2	87	20	23.0
12. Medway	47	202	42	45.2	2.4	7.1	54.7	48	62.5	0.0	16.6	79.1	90	61	70.0
13. Millis	58	139	37	10.8	0.0	2.7	13.5	27	44.5		14.8	59.3	64	21	35.9
14. Natick	46	127	109	16.5	0.0	6.4	22.9	129	34.9	0.8	11.6	47.3	238	86	36.1
15. Wayland	44	73	44	4.5	2.3	20.4	27.2	57	12.3	1.8	21.1	35.2	101	52	31.7
16. Woburn	53	160	126	6.3	0.0	4.8	11.1	112	30.3	0.9	8.9	40.1	238	39	23.5
Group 40-60		151	576	19.2	0.5	11.7	31.4	568	35.7	0.5	14.6	50.8	1,144	470	41.2
17. Bellingham	35	183	7	42.9	0.0	0.0	42.9	13	38.5	0.0	15.4	53.9	20	10	50.0
18. Carlisle	33	210	6	16.7	0.0	33.3	50.0	12	50.0	0.0	33.3	83.3	18	13	72.2
19. Dedham	22	522	35	0.0	0.0	2.9	2.9	127	11.0	0.8	11.8	23.6	162	31	19.1
20. Framingham	40	99	151	14.6	0.0	5.3	19.9	230	21.3	0.4	8.2	30.4	381	100	26.0
21. Norfolk	31	213	23	26.1	0.0	8.7	34.8	51	35.3	0.0	9.8	45.1	74	31	41.9
22. Sherborn	33	147	24	45.8	0.0	20.8	66.6	48	43.7	0.0	10.4	53.1	72	42	58.3
23. Westwood	39	243	37	5.4	0.0	2.7	8.1	57	1.8	0.0	5.3	7.1	94	7	7.5
24. Winchester	25	181	40	17.5	0.0	15.0	32.5	119	20.2	1.7	11.8	33.7	159	53	33.3
Group 20-40		187	323	16.1	0.0	7.7	23.8	657	21.0	0.6	10.3	31.9	980	287	29.3
25. Arlington	7	196	8	37.5	0.0	25.0	62.5	100	55.0	0.0	28.0	83.0	108	86	76.8
26. Canton	5	158	9	0.0	0.0	11.1	11.1	160	7.5	0.0	6.9	14.4	169	24	14.2
27. Lexington	9	126	19	36.8	0.0	15.8	52.6	202	76.7	2.0	33.2	111.9	221	235	106.8
28. Lincoln	9	233	8	12.5	0.0	0.0	12.5	85	56.5	1.2	25.9	83.6	93	72	77.5
29. Milton	0	—	1	0.0	0.0	0.0	0.0	243	4.1	0.0	3.7	7.8	244	19	7.8
30. Sharon	4	300	5	20.0	0.0	0.0	20.0	115	14.8	0.8	10.4	26.0	120	29	24.2
31. Walpole	5	98	10	0.0	0.0	0.0	0.0	186	10.7	0.0	5.9	16.6	196	31	15.7
32. Waltham	1	—	4	25.0	0.0	50.0	75.0	308	43.2	1.0	18.9	63.1	312	194	65.5
Group 0-20	4	168	64	18.7	0.0	10.9	29.6	1,399	32.0	0.6	15.2	47.8	1,463	690	47.0
Total	34	201	1,484	14.7	0.2	10.6	25.5	2,836	30.0	0.6	13.8	44.4	4,320	1,637	37.9

paring the performance of those transformers protected with those not protected.

The data collected had been tabulated for the areas to be protected. Records of blown fuses, coil, lead, bushing and terminal board troubles comprised part of the data. Previous to the storm season, all lightning arrester grounds were regularly measured for ground resistance and those over 250 ohms were treated with salt and water and/or had additional rods driven in an attempt to lower them.

The resulting tabulation is shown in Table I. From this table it would appear that the installation of lightning arresters on certain transformers had decreased all types of lightning troubles on these transformers by 40 per cent and all troubles except those classified as miscellaneous, by 50 per cent.

A study was made of the effect of lightning arrester density per unit area on the transformer lightning troubles. The troubles per one hundred transformers were plotted against the lightning arrester locations per square mile, the towns on the system being taken as the unit areas. This graph is shown in Fig. 1, and indicated a distinct improvement as the density increased which seems to check the conclusion reached by Mr. D. W. Roper.[2]

The effectiveness of various values of ground resistance was studied by the method shown in Fig. 2. It appears from this that values of ground resistance from 100 ohms to 2,000 ohms have little if any effect on the

2. *Studies in Lightning Protection on 4,000-Volt Circuits*, by D. W. Roper, A.I.E.E. Trans., V. XXXV Part 1, p. 655 and V. XXXIX Part 2, p. 1895.

number of troubles. In the course of discussion of these data the question was raised as to whether the ground resistance offered to 60-cycle secondary current which was used for testing might be different from that offered to lightning waves. The question was taken to the manufacturers and an investigation made by them showed that resistance values offered to lightning waves are appreciably less than those offered to 60-cycle currents.[3] This may account to a certain extent for the arresters. The fact that proportionately more troubles occurred on transformers 5 kva. and smaller, and that in general the smaller transformers are more remote from maintenance headquarters, together with the improvements shown with increased arrester density, led to the decision that all transformers in the towns in the protected area should ultimately be protected.

As a further result of the studies and in an effort to apply the new program most effectively all locations which were

TABLE II—SUMMARY OF LIGHTNING EXPERIENCE IN PROTECTED AREA

Year	No. of Weather Bureau lightning observations	% protection	Av. grd. res	Trans. with L.A.'s: No. of trans.	Trans. with L.A.'s: Troubles /100 trans.	Trans. with L.A.'s: Troubles /100 trans. /100 W.B.O.	Trans. without L.A.'s: No. of trans.	Trans. without L.A.'s: Troubles /100 trans.	Trans. without L.A.'s: Troubles /100 trans. /100 W.B.O.	All transformers: No. of trans.	All transformers: Troubles in year	All transformers: Troubles /100 trans.	All transformers: Troubles /100 trans. /100 W.B.O
1927	144	34	201	1,484	25.5	17.7	2,836	44.4	30.8	4,320	1,637	37.9	26.3
1928	82	38	210	1,805	9.9	12.1	2,970	13.9	17.0	4,775	600	12.6	15.4
1929	126	49	196	2,407	12.1	9.6	2,487	38.0	30.2	4,894	1,239	25.3	20.1
1930	118	56	214	2,930	15.7	13.3	2,329	22.6	19.2	5,259	987	18.8	15.9
1931	114	71	234	3,781	4.2	3.7	1,562	7.6	6.7	5,343	278	5.2	4.6

relative effectiveness of ground connections having a high 60-cycle resistance.

1928 Study

The study was continued, and more lightning arresters were installed. This year the lightning storms were much less frequent than in the previous year resulting in only about one-half as many transformer troubles as in 1927. The summary of troubles for this year is presented in Table II which indicated that the troubles with protected transformers were considerably less than the troubles with unprotected transformers. The effect of lightning arrester density and of ground resistance was again studied with results substantially as in 1927.

1929 Study

As a result of the experience of the previous two years, lightning arresters were installed at a more rapid rate and ground resistances up to 2,000 ohms for transformers larger than 10 kva. were accepted, although as before salt treatment was given where possible in an endeavor to lower the resistance of such installations.

The same type of tabulation has been made as for the previous years a summary of which is given in Table II. This again shows even more strikingly the effectiveness of protection as in this year there was proportionately more than three times as much trouble on unprotected transformers as on protected ones.

An analysis of the troubles with transformer by sizes showed that while transformers, 5 kva. and smaller, constituted slightly less than 30 per cent of all the transformers, they accounted for more than 50 per cent of the troubles.

1930 Study

Three consecutive years had apparently shown the effectiveness of the protection afforded by lightning

3. "Impulse Characteristics of Driven Grounds," by H. M. Towne, *G. E. Review*, November 1928.

not protected and where trouble occurred more than twice in 1929, were equipped with arresters. Also a small group of towns which had experienced excessive lightning troubles were selected and arresters were added to give 100 per cent protection before the 1930 lightning season.

The map Fig. 3 shows the proportion of transformers protected by lightning arresters in the various towns as of 1930. The summary of troubles for this year is shown in Table II.

As 100 per cent protection is approached, it is readily seen that the means of comparing the effectiveness of

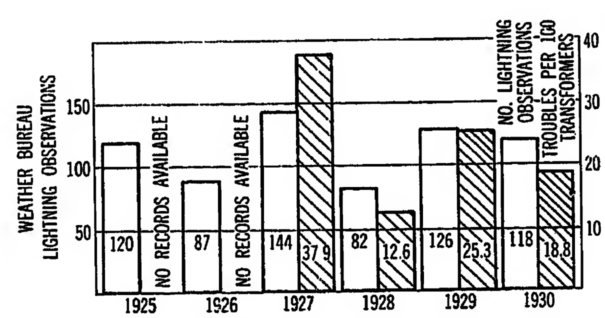

FIG. 4—WEATHER BUREAU LIGHTNING OBSERVATIONS COMPARED TO TRANSFORMER TROUBLES 1925-30

the work tends to disappear and a need for some other measure to show the progress being made becomes evident. The Weather Bureau records observations of lightning storms from several stations in and about our territory. The observations reported have been totaled and called the storm severity factor. This factor is used as a divisor to modify the trouble rate in an attempt to render them comparable.

The map, Fig. 3, locates these observation points, and Fig. 4 gives the record each year compared with the troubles in the same year.

The curve indicating the improvement following

the application of arresters is shown in Fig. 5, the rate of troubles modified by the storm severity factor is plotted against arrester protection in per cent. Extrapolation of the trend gives an indication of the improvement that may be expected by further additions of lightning arresters. As will be noted, this trend for the area considered is shown as a straight line.

The other curves in Fig. 5 showing an individual town and a group of towns are given to indicate the effect of 100 per cent protection in lowering the trouble rate. These towns were selected for complete protection on account of the severity and frequency of storms in their locality.

Using this expectation curve as a basis, it can be shown for this system that the annual saving in cost of maintenance to be expected by the decrease of troubles anticipated by protection of all the remaining transformers in the area will be sufficient to finance the investment required. Additional gain will be realized in decreased customer outage and decreased handling and overhead expenses which were not included in the cost analysis.

The investigation in 1930 furnished additional data for consideration and indicated that the shielding effect of structures and other conductors may have a more pronounced effect in protecting transformers and fuses against lightning outage than had been previously recognized. In support of this, Figs. 6 and 7 show respectively the troubles *vs.* arrester density per square mile, 1927 to 1930, and trouble *vs.* population density

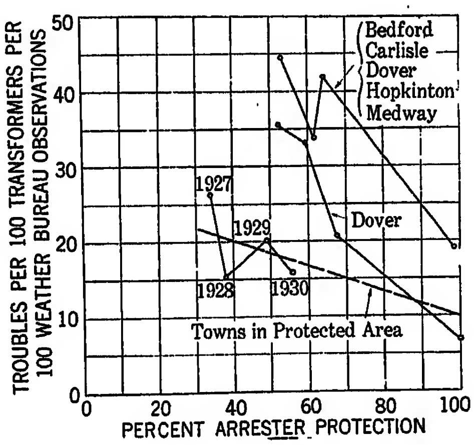

FIG. 5—VARIATION OF TROUBLE RATE (CORRECTED FOR VARIATION IN NUMBER OF WEATHER BUREAU OBSERVATIONS) WITH PER CENT PROTECTION 1927-30

per square mile for 1930. Since population density is a rough measure of the shielding afforded by buildings, the shielding may be a factor governing the trend of Fig. 7. This should be interpreted as meaning that the trouble rate in any area is the result of combination of the effects of shielding and arrester density, each of which contributes its share in the final result.

In 1929, it was learned that transformers of small sizes were particularly susceptible to lightning outage. The 1930 analysis has brought out the same condition but more strikingly. Sixty-seven per cent of the total troubles was on transformers of 5 kva. and smaller. This group constitutes 28.5 per cent of the total number of transformers.

In Fig. 8, is presented a comparison of the effect of arrester ground resistance on the efficiency of lightning arresters. As previously mentioned, the average ground resistance is high, being over 200 ohms. This curve

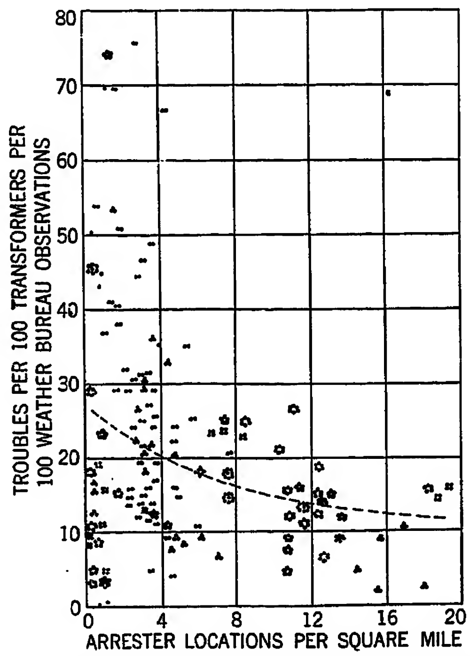

FIG. 6—VARIATION OF TROUBLE RATE WITH LIGHTNING ARRESTER DENSITY 1927-30

Note: Individual points or groups of points represent the observations in a single town; the number of points in any group being approximately proportional to the number of transformers in the town

covers the four years of the experience records. On resistances below 100 ohms, it is found that decreased resistance makes a definite improvement in the effectiveness of arresters, whereas above that point our experience has indicated that the effectiveness is not materially reduced by high ground resistance. The upper horizontal line on Fig. 8 shows the average trouble intensity for unprotected transformers; compared with the curve it has been concluded that arresters even with very high ground resistances give valuable protection.

As stated previously, lightning arresters of three manufacturers were used. Records of troubles have been segregated and tabulated by makers for the years 1927-30 and are shown in Table III. From the table it appears that for our conditions there is little to choose between them.

During 1930 careful inspections were made of nearly all the transformers where fuses were blown during lightning storms. Evidence of arcing was found in nearly every case. The arcing seemed to be concentrated on those transformers which were of more or less ancient design with small primary bushings, insufficient

internal clearances, primary terminal boards, etc. Tabulation of the results indicated that transformers made previous to 1910 gave several times as much trouble as those manufactured since then, and inasmuch as previous to this date the use of high loss iron for the transformer cores was the rule, the policy has been adopted of eliminating these old transformers from the system. All other transformers passing through the shop are rebuilt to improve the internal clearances and are equipped with modern bushings.

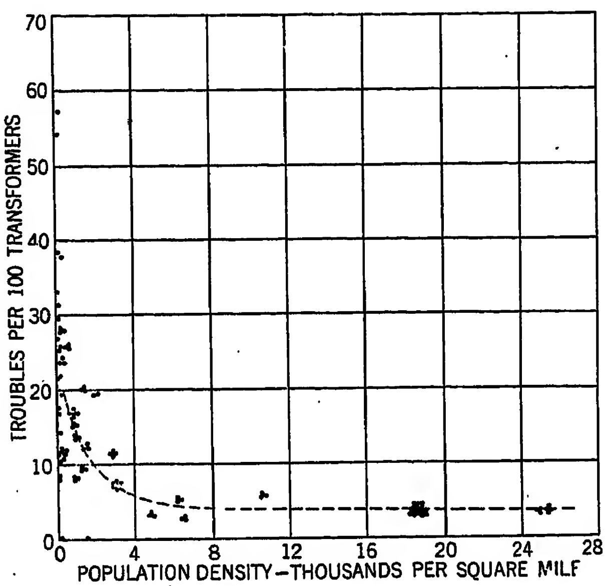

Fig. 7—Variation of Trouble Rate with Population Density 1930

Note: Individual points or groups of points represent the observations in a single town; the number of points in any group being approximately proportional to the number of transformers in the town

1931 Study

While the data for the year 1931 have not been carefully studied on account of lack of time the summary of the record is shown in Table II. A marked decrease in the total number of troubles as well as in the trouble rate will be noted. Again the rate of trouble on protected transformers is less than half that of the unprotected. The marked decrease in troubles is due in part to the rebuilding of about 25 per cent of the transformers which provided them with new bushings and the removal from the system of a large percentage of the small transformers with inadequate clearances and which were built previous to 1910.

It should be noted that the improvement in the operation of the protected transformers in general remains the same as in previous years even with nearly all the small trouble making transformers removed from the system.

TABLE III—TROUBLES FOR 100 INSTALLATIONS OF LIGHTNING ARRESTERS
(By Manufacturer)

Manufacturer	A	B	C	Average
1927	27.1	13.5	20.6	14.1
1928	16.2	4.7	5.6	9.8
1929	12.6	10.6	12.7	11.7
1930	14.5	16.6	15.2	15.7
Average	16.9	12.3	15.3	14.2
Total locations				
1930	1,109	1,452	380	2,941

Conclusions

1. Experience has indicated that the application of lightning arresters to line transformers in areas affected by lightning reduces the trouble rate by about 50 per cent.

2. Variation in ground resistance within the values readily obtainable in this territory has slight effect on the efficiency of the arrester.

3. The value of treating grounds or the installation of multiple grounds in an effort to lower resistance is questionable unless by so doing the resistance can be decreased to a value approximately 100 ohms or less.

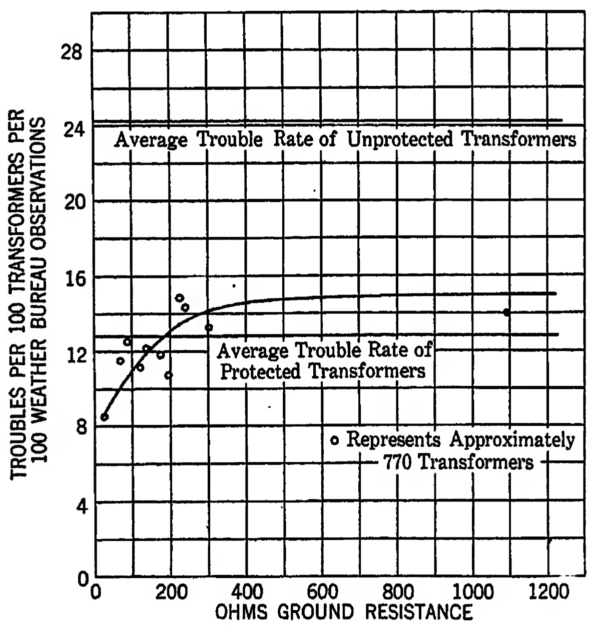

Fig. 8—Variation of Trouble Rate with Ground Resistance 1927-30

4. Insufficient electrical clearances in the smaller and older transformers are an important source of lightning trouble. Larger bushings, and greater clearances are clearly indicated as a necessary feature of correct transformer design.

Discussion

For discussion of this paper see page 271.

Distribution System Lightning Studies
By Philadelphia Electric Company

BY H. A. DAMBLY,* H. N. EKVALL,* and HOWARD S. PHELPS*
Member, A.I.E.E Associate, A.I.E.E. Associate, A.I.E.E.

Synopsis.—In the analysis of distribution lightning problems, many factors must be considered, and long-time experience is necessary to permit reliable conclusions. Philadelphia Electric Company studies indicate that service interruptions due to primary distribution system trouble are in a large part due to lightning. Primary system trouble is found to cause far more customer interruptions than secondary system trouble.

* * * * *

Introduction

INVESTIGATIONS of lightning troubles occurring on the distribution systems have been conducted by the Philadelphia Electric Company since 1921. The purpose of these has been to determine:

a. The magnitude and nature of the trouble in various localities.

b. Effectiveness of lightning arresters under field conditions.

c. Ways and means for improving service continuity.

As experience was gained, studies were broadened to cover a large number of the factors which appeared to have an important bearing on the problem.

During the interval 1921-1929 inclusive, investigations were confined to Philadelphia. In 1930 they were extended to all parts of the system, which now includes approximately 23,000 aerial transformers. The territory served covers approximately 1,900 sq. mi., which for operating purposes is divided into six divisions, as indicated in Fig. 1. The density of population ranges from sparsely settled rural districts to densely settled city areas.

The majority of the transformers is single-phase with the secondary neutral grounded at customers' services to the water system or to driven grounds. Where driven grounds are used, outside of Philadelphia the neutral is also grounded at the transformer or at the adjacent pole. Transformer cases are not grounded.

For the system as a whole, arresters are installed on approximately 50 per cent of the transformers. In Philadelphia and Delaware Divisions, however, approximately 25 per cent are so equipped. In general, no arresters are installed for line protection except at aerial-to-underground terminal poles. Arrester grounds in all divisions average 100 to 150 ohms.

Lightning Studies—Philadelphia Division 1921-1929

During this period, investigations were made of lightning trouble on transformers in Philadelphia where the distribution system is 2.3 kv. two-phase, ungrounded. A material improvement was accomplished in the first few years of that period probably due in great part to gradual changeover from small to large fuses on all transformers. Other changes, contributing to further reductions in trouble, were (a) installation of arresters in areas known to be particularly susceptible to lightning trouble, (b) replacement of iron fuse boxes, with boxes of porcelain or other moulded insulating materials, (c) removal of high terminal boards in transformers, and (d) gradual growth of the system necessitating larger transformers which experience indicates are less susceptible to trouble.

Investigations were confined to analyses of fuse blowings and transformer failures. Comparisons of trouble

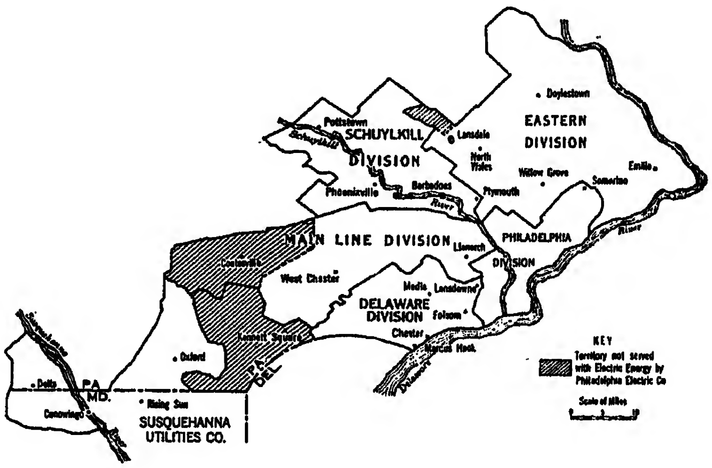

FIG. 1—1930 DIVISIONAL OPERATING BOUNDARY MAP
Philadelphia Electric Co. and Susquehanna Utilities Co.

on protected and unprotected transformers (reduced to cases of trouble per 100 transformers in service) appeared to indicate that arresters were not providing satisfactory protection. This was attributed to the relatively high resistance of the arrester grounds which averaged well over 100 ohms.

Lightning Studies—All Divisions, 1930-1931

In 1930, the studies were broadened to include many factors which from experience, appeared to be of major importance to the problem. Also, these studies were extended to the territory of the former Philadelphia Suburban-Counties Gas and Electric Co. and of the Susquehanna Utilities Co., which had become a part of

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*Philadelphia Electric Company, Philadelphia, Pa.

Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 25-29, 1932.

the Philadelphia Electric System. This permitted investigations on a variety of systems as follows:

a. 2.3 kv., two-phase, three-wire, ungrounded.

b. 2.3 kv., three-phase, three-wire, ungrounded, delta-connected.

c. 4.1 kv., three-phase, four-wire, grounded, star-connected.

d. 6.6 kv., three-phase, three-wire, ungrounded, delta-connected.

The first is used in the Philadelphia and Delaware Divisions, while the second and third are used in the Eastern, Main Line and Schuylkill Divisions. (See Fig. 1.) The 2.3-kv., three-phase, and the 6.6-kv., three-phase systems are used in the Susquehanna Utilities Co.

From observations thus far it has been impossible to detect any difference in susceptibility to lightning between grounded and ungrounded systems. This will be closely watched in future work.

Major Factors Investigated During 1930-1931

The following factors which appear to be of major importance to the problem as a whole will be discussed:

1. Size of transformer
2. Age of transformer.
3. Arrester protection of transformer.
4. Fuse protection of transformer.
5. Shielding—exposed and unexposed locations.
6. Lightning storm severity.
7. Effect of ground resistance.
8. Relation of primary (2.3 kv.) to secondary (115/230 volt) trouble.
9. Analysis of customer-hour interruptions.

Discussion of these items will be based largely on experience in the Philadelphia Division, for which more complete information was obtained than for other areas.

Size of Transformers

The amount of trouble experienced in all divisions in 1930 decreased with increasing size of transformer, as indicated in Fig. 2. For all transformer sizes, fuse and fuse box trouble was found to be greater than transformer bushing, lead or winding trouble. Similar conditions were also found for all divisions in 1931.

The greater trouble on the small transformers is believed largely due to (a) smaller clearance between leads and case, and (b) smaller bushings, thus permitting more flashovers at these points with resultant short circuits. Lead trouble and winding trouble are compared in Fig. 4.

Therefore reduction in trouble should result from replacement of the smaller transformers with larger ones or with those of like size of recent design.

Age of Transformer

From limited information obtained in 1930, the age of

TABLE I—SUMMARY OF TRANSFORMER LIGHTNING TROUBLE—1930

Division	Transformers: Number in service	Transformers: Average size-kva.	Total troubles	Troubles per 100 transformers: Fuse and fuse box	Troubles per 100 transformers: Transformer	Troubles per 100 transformers: Total
Philadelphia	8,467	32.8	230	1.5	1.2	2.7
Eastern	4,204	9.5	250	4.2	1.8	6.0
Schuylkill	3,830	9.7	69	0.6	1.2	1.8
Main Line	3,043	10.7	220	5.1	2.1	7.2
Delaware	2,299	22.3	20	0	0.9	0.9
Susq. Utilities	958	6.0	275	26.2	2.5	28.7
Total system	22,801	19.5	1,064	3.2	1.4	4.6

TABLE II—SUMMARY OF TRANSFORMER LIGHTNING TROUBLE—1931

Division	Transformers: Number in service	Transformers: Average size-kva.	Total troubles	Troubles per 100 transformers: Fuse and fuse box	Troubles per 100 transformers: Transformer	Troubles per 100 transformers: Total
Philadelphia	8,312	32.8	183	1.3	0.9	2.2
Eastern	4,581	10.1	317	3.1	3.8	6.9
Schuylkill	3,863	10.2	190	2.8	2.2	5.0
Main Line	3,197	11.4	221	4.2	2.7	6.9
Delaware	2,475	20.3	49	0.2	1.8	2.0
Susq. Utilities	1,182	6.0	96	7.2	0.9	8.1
Total system	23,619	19.2	1,056	2.5	2.0	4.5

Summary of Lightning Trouble—All Divisions, 1930-1931

During 1930, approximately 5 per cent of the transformers on the combined system experienced lightning trouble. Of these, 68 per cent represents transformer fuse and fuse box trouble, and the remainder transformer (bushing, lead or winding) trouble. In 1931 a similar condition was found. This experience is summarized in Tables I and II.

The higher rates in several of the suburban divisions than in Philadelphia are believed due in part to the use of smaller transformers which influence both fuse and transformer troubles. In Delaware Division the rate was lower than in Philadelphia due probably to less severe storm conditions.

transformers based on date of manufacture (information from serial number, not date installed) appears to be of importance only on sizes of 5 kva. and less. For these, it is believed the newer transformers are less susceptible to lightning than the older.

Arrester Protection of Transformers

Analysis of arrester performance, neglecting transformer size, has shown consistently during the past five years that arresters apparently effected little reduction in trouble. However, the same data, when analyzed with respect to transformer size, based on the rate of

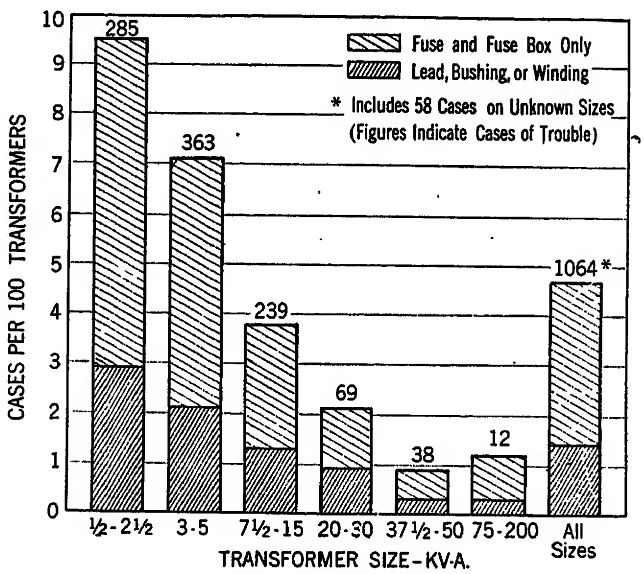

Fig. 2—Fuse and Transformer Lightning Troubles

Aerial distribution type—Philadelphia Electric Co. System—1930

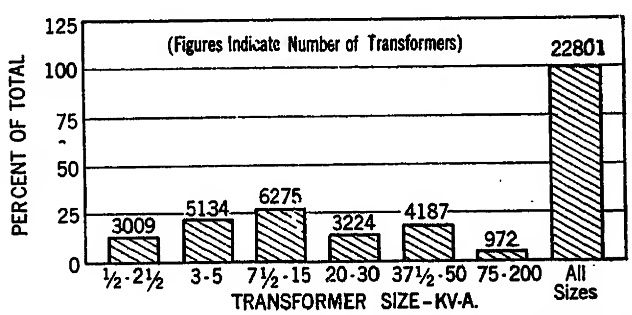

Fig. 3—Aerial Distribution Transformers in Service as of Aug. 1, 1931

Philadelphia Electric Co. System—1930

troubles on various size-groups, indicates that transformers of 15 kva. and less were not materially benefited, but that those above 15 kva. showed a considerable reduction in trouble as indicated in Fig. 5. These observations result from studying all cases of trouble, about 1,000 in number, on approximately 2,500 protected and 5,500 unprotected transformers fairly evenly distributed throughout Philadelphia Division. The significance of the latter is that protected and unprotected transformers were subjected to essentially the same storm conditions.

Reductions shown in Fig. 5 were determined by comparing the number of cases of trouble on protected

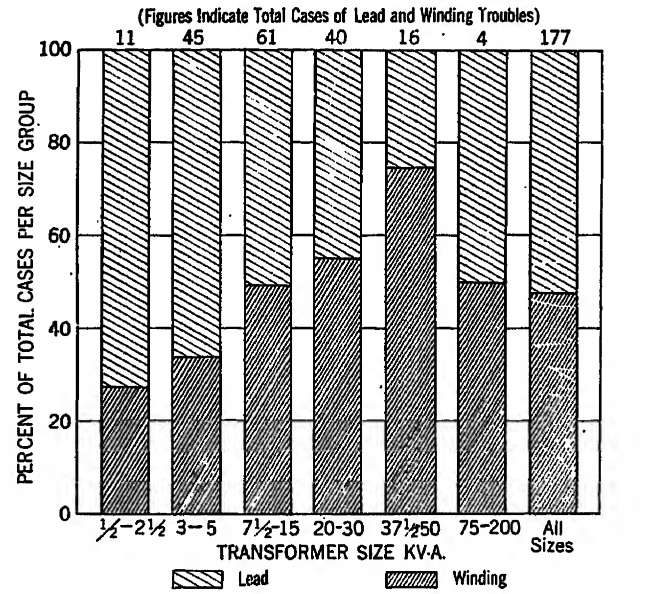

Fig. 4—Lead and Winding Trouble Due to Lightning

Aerial distribution transformers—Apr. 7, 1930 to Sept. 1, 1931, Philadelphia division

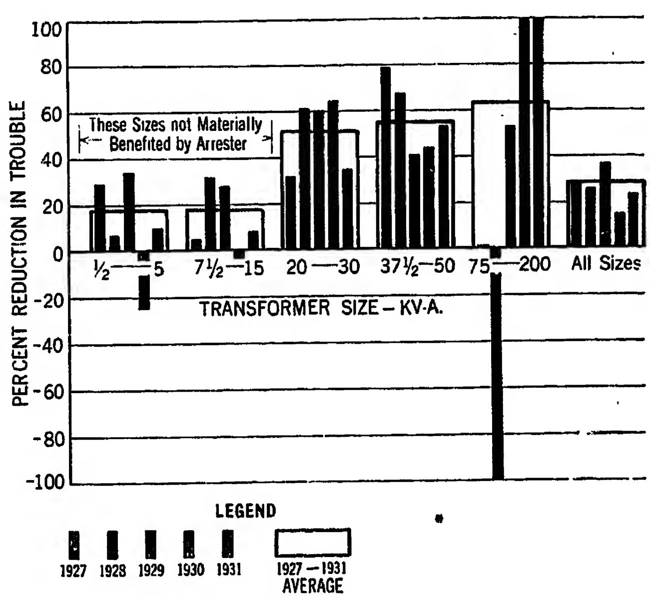

Fig. 5—Reduction in Trouble by Lightning Arresters

Yearly and average 1927—1931 Philadelphia division

transformers with the number which probably would have occurred had the transformers been unprotected. By this method variations in storm conditions from year to year did not affect the analysis.

Erroneous conclusions concerning overall protection may result by calculating protection from the rate of trouble on protected and unprotected transformers, without regard to the number of transformers or cases of trouble in the individual size groups; the latter method does not properly weight the difference in performance of various size transformers. The particular data under analysis shows 28 per cent probable reduction in trouble by the method used and 10 per cent if such weighting were neglected.

The apparent poor performance of arresters on small transformers may be due to the relatively low voltage breakdown of leads to case, resulting from restricted clearances. Thus, the breakdown voltage of the transformer leads may approach too nearly that of the arresters. It is believed this applies particularly to older transformers.

The foregoing experience was obtained entirely on the two-phase system. For the three-phase systems, the study has not advanced sufficiently to permit a similar analysis.

Fuse Protection of Transformers

Fuse size has an important bearing on the number of fuse operations during lightning storms. These were materially reduced in Philadelphia Division and Susquehanna Utilities Co. by changing from small to large fuses without appreciably increasing transformer failures.

The former practise was to protect against overloads by fusing at one ampere per kva. of transformer capacity. Fusing against short circuits is now general throughout the system.

Shielding—Exposed and Unexposed Locations

Thus far it has not been found possible to establish any satisfactory relation between trouble experienced from lightning, and shielding provided by trees, tall buildings, topography and similar factors. However, it is felt that this may be a significant factor, since where shielding prevails, less lightning trouble is likely to result.

Lightning Storm Severity

Approximately 45 per cent of all distribution system lightning trouble for 1931 to September 1, occurred during one storm (July 14) although 20 or more other storms occurred during this period. This, with similar experience in previous years, indicates the number of storms to be an unsatisfactory measure of the overall lightning severity for a given year.

Although storm severity is believed to have a fairly definite relation to the amount of trouble, personal observations and impressions have not been found satisfactory for estimating lightning severity. A storm severity meter in process of development by the General Electric Co. appears to hold promise as a means for obtaining reliable data.

Effect of Ground Resistance

Theoretically, the lower the arrester ground resistance the greater will be the reduction in surge voltage upon arrester operation. This, together with the favorable performance of arresters on the Company's 13.2 kv. lines, with grounds reduced to 15 ohms or less, is largely responsible for the effort directed to improving distribution grounds.

Measurements on single driven grounds widely distributed throughout the system indicated an average resistance of the order of 100 ohms. Accordingly, consideration was given in 1931 to the following methods of improving grounds.

1. Salt Treatment.
2. Multiple Ground Rods.
3. Connection to Water System.
4. Connection to Secondary Circuit Grounded Neutral.

Methods 2 and 4 were experimented with as discussed below:

Method 2—Multiple Ground Rods. In northeast Philadelphia where lightning trouble was serious, 345 installations of ground rods in multiple with existing arrester grounds were completed in July 1931. With a maximum of four additional rods (10 ft. long by ¾ in. diameter) per location, it was possible to reduce 45 per cent of the grounds, many of which originally exceeded 50 ohms, to less than 15 ohms, and all to less than 50 ohms.

To September 1, 1931, eight cases of trouble occurred at these locations. Of these eight cases, seven occurred where grounds exceeded 15 ohms. Expressed as troubles per 100 transformers, these data indicated that locations with grounds below 15 ohms experienced about 13 per cent as much trouble as those having grounds above 15 ohms. However, this is based on very short experience and therefore should not be considered conclusive.

Multiple rods were also installed in an area outside of Philadelphia where lightning troubles were even more serious than in the Philadelphia area. Here the 266 installations were completed in June, 1931. Essentially the same reduction in resistance was obtained as in Philadelphia. To September 1, 20 cases of trouble occurred at these locations. However, approximately the same rate of trouble occurred at locations with high as with low resistance.

The foregoing shows a marked difference in experience in the two multiple rod areas. This is believed due to the relatively small transformers in the area outside of Philadelphia, averaging about 4 kva., as compared with 15 kva. in Philadelphia. As previously discussed, studies have shown that little lightning protection can be obtained for the small transformers.

Method 4—Connection to Secondary Circuit Grounded Neutral. Because of its low cost and added advantage of tending to equalize surge potentials on primary and

secondary sides of the transformer during arrester operation, connection between the arrester ground wire and secondary circuit grounded neutral has been studied. Trial installations of this connection, hereafter called the "neutral tie" were completed early in June, 1931 at 151 locations, involving 179 transformers. For comparative results these were concentrated in an area adjacent to where multiple rods were installed in Philadelphia, and in which lightning troubles have been equally severe. The scheme is shown in Fig. 6.

The neutral tie was applied only where a prescribed secondary ground grid existed. This was defined as locations where the ground resistance of the secondary neutral measured less than 15 ohms and where the secondary circuit fed 10 or more customers whose service neutrals were grounded to water pipes. Existing arrester grounds were retained, although where of high resistance their protective value is doubtful. The resulting ground resistance was in all cases less than 10 ohms as determined by megger measurement.

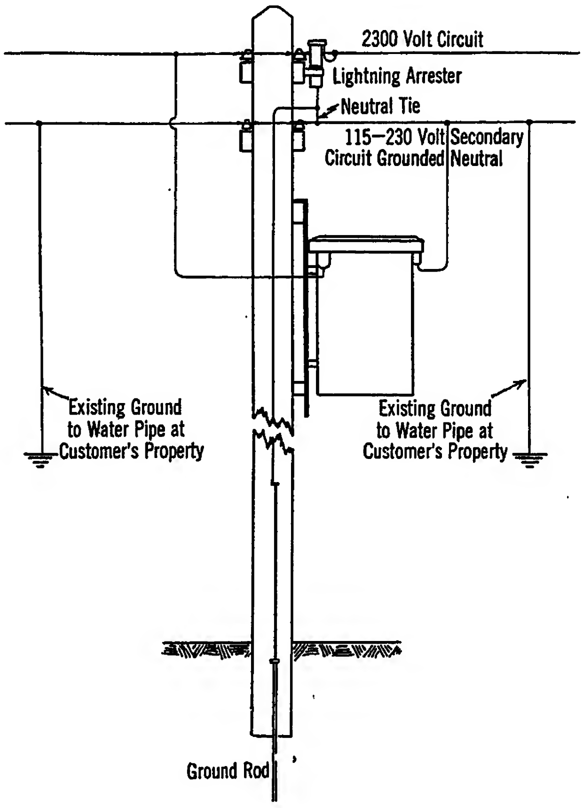

FIG. 6—SCHEMATIC DIAGRAM FOR INTERCONNECTING ARRESTER GROUND WIRE AND SECONDARY CIRCUIT GROUNDED NEUTRAL

Philadelphia division

To September 1, only one case of trouble, a transformer fuse blowing, occurred at neutral tie locations. This was not accompanied by trouble on the secondary circuit or customers' equipment. In this area 94 protected transformers without the neutral tie (because secondary circuit conditions did not meet the requirements) had approximately the same rate of trouble as those with the neutral tie. In the same area, 754 unprotected transformers experienced considerable trouble, thus indicating the area had been exposed to lightning storms of moderate severity.

Although this short experience indicates the feasibility of the neutral tie, observations over a long time and with a larger number of installations must be obtained before dependable conclusions may be drawn.

Analysis of customer meter trouble due to lightning during the storm of July 14 indicated less trouble on secondary circuits fed from transformers with arresters connected to the neutral than on those from unprotected transformers. This indicates the neutral tie did not aggravate secondary troubles and therefore, imposed no additional hazard on persons or property.

RELATION OF PRIMARY (2.3 KV.) TO SECONDARY (115/230 V.) TROUBLE

To determine the relative magnitude of primary and secondary system troubles during lightning storms an analysis of these was made for the storm of July 14. The trouble during that storm was selected for study because there was an unusually large amount of it and because information concerning it was concentrated in the records. It was later found that approximately 70 per cent of the total 1931 primary system trouble in Philadelphia occurred during that storm. The troubles together with the estimated number of customer-interruptions are summarized in Table III.

TABLE III—*PRIMARY AND SECONDARY LIGHTNING TROUBLE AND ESTIMATED CUSTOMER INTERRUPTIONS DUE TO STORM ON 7-14-31

Philadelphia Division

Classification of trouble	Number of cases	Estimated customer interruptions
Primary system (2.3 kv.)		
Transformer fuse and fuse box	69	4,140
Transformer winding	30	1,800
Transformer lead	27	1,620
Primary wires down	27	4,500
	153	12,060
Secondary system (115/230 v.)		
Customers' service fuses blown	1,200	1,200
Customers' defective apparatus, appliances, cords, and wiring	300	300
Meters damaged	138	138
Outside (external to service connections)	90	90
Service pipes	2	2
	1,730	1,730

*Excludes service lost due to circuit interruptions at substations.

The relative magnitude of primary and secondary trouble might also be compared on a customer-hour-interruption basis. However, the duration of the two should be essentially the same as far as nature of repairs is concerned.

Correlating the 138 cases of customers' meter trouble with the 153 cases of primary system trouble shows that only two of the former occurred on secondary cir-

cuits fed by transformers experiencing primary trouble. Accordingly, secondary circuit trouble must be due largely to lightning disturbances originating on that circuit.

It is evident from the causes of customers' interruptions that greater overall improvement in service continuity may be accomplished by attacking the primary rather than the secondary situation. However, from the viewpoint of service to the individual customer, interruptions from secondary trouble are just as important as those due to primary trouble. Consequently, efforts should also be directed toward reducing secondary trouble.

Analysis of Customer-Hour Interruptions

Primary circuit and individual transformer interruptions exceeding five minutes, throughout Philadelphia and Suburban Divisions in 1931 (to September 1), were analyzed to determine the relative magnitude of (a) those during lightning storms with those during other periods, and (b) those directly due to lightning disturbances with those due to other causes such as wind, trees, etc., during lightning storms.

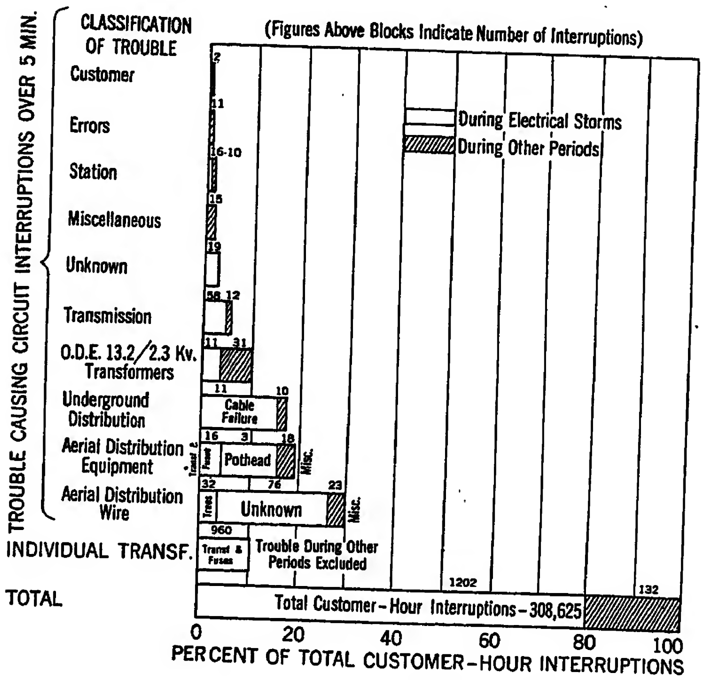

Fig. 7—Estimated Customer-Hour Interruptions

Due to primary distribution system interruptions Jan. 1 to Sept. 1, 1931 Philadelphia and suburban divisions

Although circuit interruptions of five minutes or less, many of which were only momentary, represented approximately 80 per cent of the total, they were considered to cause only minor inconvenience compared to those of longer duration. Consequently, the analysis was confined to those exceeding five minutes.

As a measure of the inconvenience to the customer, all interruptions were expressed in customer-hours. The duration of circuit interruptions was taken as the time during which the circuit was off at the substation. The duration of interruptions due to individual transformer trouble (not causing primary circuit interruptions) was the time between receipt of trouble report and time "reported cleared." Averages of transformers per circuit, and customers per transformer based on kva. rating, were estimated for each division. The results classified according to the character of trouble are presented in Fig. 7.

This shows that 80 per cent of the total customer-hour interruptions occurred during lightning storms. Of this portion approximately 85 per cent were due to four major causes, as follows:

Trouble on	Estimated customer-hour interruptions during lightning storms
1. Underground distribution	47,900
2. Aerial distribution equipment	48,500
3. Aerial distribution wires	81,600
4. Individual distr. transformers	32,600
	210,600

Nearly all of the above customer-hours attributed to 2 and 4 and an estimate of 50 per cent of those attributed to 1 are believed to have resulted directly from lightning disturbances. It may be determined from this that lightning is responsible for approximately half of all customer-hour interruptions experienced during lightning storms. It appears, therefore, that protection of distribution systems against lightning is of major importance in bettering service continuity.

Aerial distribution wire trouble also contributes substantially to interruptions during lightning storms. However, most of the wire troubles are believed due to causes other than lightning, such as falling trees. Tree conditions, while frequently difficult to overcome, appear to require increased attention to minimize interruptions. Tree troubles of an unknown nature are believed responsible for a large part of the conditions marked "Unknown" on Fig. 7.

Summary and Conclusions

From the foregoing experience, the following conclusions are reached:

1. Annually about 5 per cent of the 23,000 aerial distribution transformers experienced lightning trouble. The small transformers have been found more susceptible than large ones. As far as practicable, the larger transformers should be used, or the older units replaced with more recent ones of the same size.

2. Difference in susceptibility between transformers of different sizes must be recognized when analyzing arrester performance.

Observations over five years show little benefit from arresters when considering transformers of all sizes collectively. However, taking size into account, these

same data indicate arresters afforded little benefit to those of 15 kva. and less, and substantial benefit to the larger sizes.

3. Many factors influence lightning trouble on distribution systems. It is important to consider all of the major ones if reasonable conclusions are to be obtained.

Also, to permit comparisons with other studies, it is important to have data reduced to a common basis. One method is to compare performance per 100 transformers.

4. Because of the many factors involved, it has not been possible thus far to determine whether there is material difference in susceptibility to lightning trouble on grounded and ungrounded systems.

5. Low ground resistance, which theoretical and field studies show to be essential to effective arrester performance, may be obtained at low cost by connecting the arrester ground wire to the secondary circuit grounded neutral where a well grounded secondary neutral grid exists.

Limited field experience shows this method to furnish satisfactory protection against transformer failure without introducing additional troubles on the secondary system.

6. Customer interruptions from trouble on the primary system far exceed those from trouble on the secondary system. Therefore, major improvement in service continuity can best be accomplished by attacking the primary situation. However, service reliability as measured by the customer is independent of the source of trouble, and consequently improvements on the secondary system cannot be neglected.

7. The number of customer interruptions of less than five minutes greatly exceeds those of more than five minutes. However, when these are expressed as customer-hour interruptions, the latter greatly exceeds the former.

8. The major number of customer-hour interruptions due to all causes occur during electrical storms. Of these, it is estimated that one-half are directly attributable to lightning disturbances.

9. In the interest of improving service continuity, lightning protection of distribution systems has been found to be of major importance. Also, it is significant that it can be justified economically only from this point of view. The important factor is the inconvenience to customers which may thus be minimized. Although intangible, this factor is nevertheless very real and should be carefully considered in establishing policies and practises in meeting the problem.

The authors wish to express their appreciation of the assistance of the Operating Department, especially Messrs. W. Foster, G. S. Van Antwerp and their associates, in accumulating the data obtained in these studies; also, to Mr. V. T. Roth, and associates in the Engineering Department for their untiring efforts in collecting and correlating the information.

Discussion

INTERCONNECTION OF PRIMARY LIGHTNING ARRESTER GROUND

(Harding and Sprague)

LIGHTNING PROTECTION FOR DISTRIBUTION TRANSFORMERS

(McEachron and Saxon)

LIGHTNING PROTECTION FOR DISTRIBUTION TRANSFORMERS

(Opsahl, Brookes and Southgate)

STUDIES IN LIGHTNING PROTECTION ON 4,000-VOLT CIRCUITS—III

(Roper)

LIGHTNING PROTECTION FOR DISTRIBUTION TRANSFORMERS

(Haines and Corney)

DISTRIBUTION SYSTEM LIGHTNING STUDIES

(Dambly, Ekvall and Phelps)

Harold C. Dean: While the authors of the several papers generally agree that interconnection of the lightning arrester ground with the grounded secondary neutral represents an important improvement in distribution system practise, they rather carefully refrain from showing that it would also be desirable to connect the transformer case to the secondary neutral. Apparently this is due to the prevailing misapprehension that grounded transformer cases would be hazardous to the linemen. Indeed Messrs. Opsahl, Brookes and Southgate dismiss the idea with the statement "The case of low-voltage class distribution transformers is left free, for the safety of the workmen who may touch it while working on the live transformer conductors" while Messrs. McEachron and Saxon conclude "nothing is to be gained with the interconnection by connecting the transformer tank to the secondary neutral, since with the tank floating, the potentials developed to tank are much less than the strength of insulation involved and the hazard to linemen is decreased."

In the New York Edison System we have found that a known hazard is to be preferred to an unknown hazard and we have adopted as a standard the grounding of all transformer cases. Where mounted on poles the transformers are located on a level with the secondary wires and five feet below the primary wires, and we require our linemen to cover up all grounded parts as well as low-voltage and high-voltage wires before doing any work on poles.

In support of our contention that it is bad practise not to ground transformer cases, I would point to the evidence presented in the papers that a large number of the transformer failures do not result in destruction of the windings, but merely result in the ground of a primary lead to the case. Due to the insulation afforded by the poles, these failures between primary leads and cases may not be detected and such cases will of course present very real hazards to linemen who get used to assuming that transformer cases are dead.

Several years ago one of our companies lost a lineman who inadvertently came in contact with a transformer case while working on a secondary wire. As a result of this, the company made a survey of all pole type transformers and found seven cases with full primary potential. Thereafter, pole type transformers were surveyed annually (at some considerable expense) and each year one or two additional installations would be found in which the transformer cases were "hot."

In 1930 The New York Edison System undertook a study looking toward the standardization of transformer installations on poles. Only four of the system companies had overhead lines and four different practises were found. With respect to grounding, we found the following practises:

1. One company connected the lightning arrester ground leads to the secondary neutral, but did not ground the transformer

cases nor install driven grounds at the transformer poles. (This had been the practise for twenty years.)

2. One company connected the lightning arrester ground leads to the secondary neutral and also to driven grounds, but did not ground the transformer cases.

3. One company connected the lightning arrester ground leads to driven grounds only and did not ground the transformer cases.

4. One company connected lightning arrester ground leads to driven grounds only and connected transformer cases to the secondary neutral only. (This had been the practise for sixteen years.)

While the basis for keeping statistical records of transformer failures had not been uniform for all the companies, and while the physical conditions such as exposure to lightning, average size of transformer and transformer fuse, system of primary distribution, etc., were not uniform, nevertheless, all available records of failures due to or suspected of being due to lightning were analyzed and showed the following averages for the years 1928, 1929 and 1930:

AVERAGE RATE PER 100 TRANSFORMERS, 1928 TO 1930 INCLUSIVE

	Transformer failures	Blown fuses	Total
Company with lightning arrester ground leads connected to secondary neutral only. Cases not grounded	0.045	1.03	1.075
Company with lightning arrester ground leads connected to driven grounds only. Cases not grounded	0.88	0.77	1.65
Company with lightning arrester ground leads connected to driven grounds only. Cases grounded to secondary neutral	0.77	4.53	5.30

It is significant that the company which connected its lightning arrester ground leads to the secondary neutral experienced about 1/20th the transformer failure rate of the two companies which depended upon driven grounds. It is also to be noted that the company which grounded its transformer cases to the secondary neutral, but failed to make a connection between the lightning arrester ground leads and the secondary neutral, blew about five times as many fuses as the companies which did not ground cases. As a result of this investigation it seemed obvious that no one company had done a complete job of grounding and that to obtain all the benefits of grounding, the following standards should be adopted for transformer installations on poles:

1. Lightning arrester ground leads shall be connected to the secondary neutral.

2. Lightning arrester ground leads shall be connected to driven grounds at the poles if there are less than two water pipe service grounds connected to the secondary neutral on the pole or poles not more than one section away from the lightning arrester.

3. Lightning arrester ground leads shall be connected to the primary neutral (if any exists).

4. Transformer cases shall be connected to the secondary neutral.

This standard has been in effect since July 15, 1931, and it is expected that all installations on the system will have been made to conform with this standard before the 1932 lightning season.

A. H. Schirmer: When a transformer fails, particularly in areas where there are no water-pipe grounds, the voltage on the secondary circuit may closely approach the primary voltage. Such excessive potentials on the secondary, combined with lightning surges, frequently cause trouble to telephone plants. Any reduction in transformer failures, therefore, will be of considerable benefit to the telephone companies.

The Bell System has been conducting lightning tests for a number of years. While these tests were not made directly on power transformers, the results obtained indicate rather definitely that in order to protect transformers against lightning surges, it is necessary to place the arrester between the primary and secondary circuit. In fact this method of protection has been used for years by the telephone company on open-wire loading coils.

The main question is: "Does such a practise make the situation less safe on the premises of the consumer?" In our opinion, connecting the arrester between the primary and secondary circuit actually makes for an increase in safety on the premises of the consumer, provided a suitable arrester is used. One of the power companies used to a limited extent an arrester consisting of a simple sphere gap connected between the primary and secondary windings. Such an arrester will, of course, protect the transformer but every time it operates, the primary voltage is directly impressed on the secondary circuit. The use of such a sphere gap will also result in excessive fuse operation. Obviously such a practise is not sound. The maximum safety is reached when we use an arrester having a current limiting element so designed that the voltage across the transformer windings is held to a value slightly below the impulse strength of the transformer. With such an arrester the lightning voltage on the secondary from a surge on the primary would be held to the lowest practical value and no power voltages of considerable magnitude would appear between the secondary circuit and ground, after all it is the excessive power voltage rather than lightning surges which make for hazard on the premises of the consumer. Furthermore, the use of an arrester which limits the voltage just enough to prevent failure of the transformer will keep fuse operation to a minimum.

In order to insure that no excessive potentials are imposed on the secondary circuit due to lightning arrester failures, the arrester should be designed so that the leakage current from normal potential will not cause excessive heating in the current limiting element, or if this is not practical, it should be designed so that the arrester will blow up or in some way open the circuit before it can introduce excessive potentials on this secondary circuit.

The use of such an arrester across the primary and secondary circuit will in our opinion be safe and in a large measure eliminate the failure of transformers.

F. W. Peek, Jr.: There is one subject that is not specifically considered in any of the papers, but upon which the successful operation of the various protective schemes depends. The papers show that a strong transformer properly connected to a suitable lightning arrester is necessary. The most important factor is a well insulated transformer. The A.I.E.E. acceptance test should be a measure of the transformer insulation.

At the present time the Institute does not provide for any insulation tests other than that made at or near 60 cycles. In view of the knowledge now available, I believe that the Machinery Committee or other suitable technical committees of the Institute *should review present methods of testing with the object of devising lightning tests* if such tests seem desirable. These tests, if made, should supplement the present tests and not supersede them. *I make the suggestion for a consideration of lightning tests on transformers after years of experience with such tests made for the purpose of devising lightning proof transformers and also in making lightning tests on commercial transformers.* The first commercial tests were, in fact, reported in the *Electrical World* in August 1930. I mention these facts to show that the tests are entirely practicable.

If such tests seem advisable, I recommend that rules be made by a technical committee of the Institute because of the highly technical problems involved, not only in methods of testing, but also in methods of detecting possible damage or deterioration or incipient failures during the test. This follows because it is important that there is assurance that the transformer is as good after the test as it was before the test was made. I hope the Institute can give early consideration to this matter.

A. E. Silver: The paper by Messrs. Dambly, Ekvall and Phelps gives an excellent summary and a measure of the relative importance of types of troubles experienced on an extensive and varied distribution system. It is to be hoped that these investigations will serve as a guide for the further extension of their studies, to including especially the field of the higher distribution voltages.

In this analysis of lightning effects on the Philadelphia Electric system, the authors are to be commended for moving the main objective of their studies from the distribution transformer to the effects on service. The rapid increase of tangible results from these investigations successively for the past two years is significant. This is one of several indications that, I believe, point to a movement into a new order of distribution practises as concerns the minimizing of interruptions.

The Philadelphia Electric investigators found that at least 80 per cent of their troubles, for a given period, came from quickly disappearing causes. I would venture the guess that a large majority of the remaining 20 per cent were from causes that can be made quickly to disappear. Of course, with open-wire lines there will always be some causes that cannot be quickly removed, such as lines put out of service by falling trees and limbs, but I believe these can be made a very small percentage of the total in our eastern areas where lightning is prevalent. While it is not assured that this figure of 80 per cent plus is generally representative, I am going to use it as illustrative of the point I wish to bring out. Most of these interruptions from quickly disappearing causes, by diligent engineering attention, I believe, are capable of being so restricted as either greatly to minimize effect on service or to avoid interruption altogether.

Again, I believe the Philadelphia Electric authors are moving in a constructive direction when they attempt to evaluate causes and effects in terms of customer hour-interruptions or, in other words, to measure with the yardstick of overall economy. In these days of rigid economies, it is encouraging that most of the opportunities that offer a means of cutting down service interruptions do not entail any eventual net increase and, perhaps, a reduction of capital costs, quite aside from the reduction of revenue losses from non-delivery and the decrease of operating and maintenance costs. The directions from which I look for progress in distribution practise include:

1. Improved relaying to realize quick and dependable disconnecting of the circuit in trouble. One of the simpler ways for accomplishing this would be by utilizing residual current which would favor the grounded neutral system.

2. Perfecting and applying the reclosing circuit breaker to general use by bringing the time for the complete switching cycle (including relay action) down to something under 30 cycles. This rapid restoration of service should render the effect of most interruptions essentially negligible except for synchronous load. With more radical developments, it does not seem beyond reason that the switching cycle and equipment may be made such as to protect even synchronous load against falling out of step. Good design and sufficiently quick disconnection should essentially eliminate burn-offs, porcelain breakage and all such damage from fault current that tends to a prolonged interruption.

3. The prevention or quenching of the dynamic fault arc by local means before the circuit has been disconnected or service has been interfered with. This means very rapid deionizing of the arc path,—one possible method being the perfecting of some simple arc interrupting device.

4. Adaptation of the automatic features of secondary a-c. networks, now extensively used in high load density districts, to areas of lighter load density, including some districts served by overhead systems.

5. Self-protecting distribution transformers. This may take the form of suitably related insulation or the simplification of lightning arresters or other protective devices as an integral part of the transformer itself. Efficient grounding and connecting of the protective device to the secondary neutral will play a large part. Messrs. Harding and Sprague's paper and others in this symposium are constructive contributions in this direction.

6. Gradual system simplification through elimination of intermediate voltage transformations and circuits, in service but no longer needed, as a means of reducing the opportunities for interruptions to originate.

7. The economizing in line insulation by setting the levels to meet the duties of surges originating at intervals, dirty surface conditions, etc., but omitting any further increments against lightning spillover. In addition, the intelligent coordination of line, station and equipment insulation.

Even a part of the progress that is promised by these developments will accomplish another substantial economy because of greatly reduced demands for reserve facilities for duplicate service.

C. L. Fortescue: The opinions expressed seem to be unanimously in favor of the by-pass arrangement of lightning arresters and I think the conclusions are correct.

In the old method of protecting transformers the arresters were connected between the high-voltage lines to a ground which was assumed to be of low enough value to reduce the surge to a safe value for the transformer windings but no thought was taken of the effect of the grounding lead which, on account of high surge impedance, would with steep wave fronts produce a high potential between true ground and the line, no matter how effective the arresters might be, nor was any consideration given to the difficulty of getting very low grounds in some territories. Under the conditions imposed by the old rule the transformer case would take up an intermediate potential between that of the high-voltage winding and the low-voltage winding. The low-voltage winding, on account of the fact that the neutral wire was solidly grounded and the secondary line wires had pretty low surge impedance, would remain practically at ground potential. There is a possibility that the difference of potential between the case and the low-voltage windings may be sufficient to cause failure of the low-voltage insulation but usually the failure takes place due to flashover of the high-tension bushing which results in the case being brought up to the potential of the high-tension winding and this in turn causes failure of the low-tension bushing so that the remaining portion of the surge is passed on to the low-tension winding. It was not always the practise to use arresters for the reason that frequently they were rendered ineffective on account of the difficulty of obtaining good grounds. According to my understanding the Safety Code does not make the use of lightning arresters mandatory for the protection of distribution transformers.

In the proposed by-pass connection the surge does not enter the transformer windings but is by-passed through the arrester to the neutral wire of the low-tension winding which is well grounded and where it can do no harm either outside or at the customer's premises because at the customer's premises it has a good ground which is obtained without difficulty. The whole transformer, including the case, is raised momentarily to the surge potential during the passage of the surge but the value of this potential is limited by the ground on the neutral wire at the customer's premises. The action of the arrester absolutely prevents any danger of the high-tension current being carried into the customer's wiring circuit which is not true in the old connection or when no arresters are used and flashover takes place over low-tension bushings which is the most frequent type of failure.

It is necessary to give some consideration to the possible value of the surge that may pass into the customer's wiring circuits. This surge will be limited to a comparatively low value by the customer's ground but consideration must be given to the length of lead between the secondary of the transformer and the customer's circuit because whatever potential appears at the transformer secondary terminals will appear in the customer's circuits and in some cases where these leads are long it may be advisable

to use some kind of arrester between lead and neutral at the premises. I believe that in general, in the average case, this will not be necessary but nevertheless it is something that ought to be kept in mind. Where there are a multiplicity of circuits leading to residences the surge impedance of these combined circuits is very low and the multiplicity of grounds also improves conditions and in such cases the arrester at the customer's premises can be dispensed with.

While customers' grounds probably have very low surge impedance, this should not be taken for granted and an investigation should be made of the surge impedance of various types of residence grounds so as to make sure that the grounding arrangements are satisfactory. I think that the surge impedance of a residence ground should be kept as low as possible. I think a reasonable value should be below two ohms. In the case of isolated residences, such as farms and so forth, ready-made grounds may not be available. Driven-grounds should then be used and since the length of line between transformer and customer's circuits is usually longer in such a case I think it advisable to use arresters at the customer's inlet. To sum up, the proposed connection assures very much better protection to the transformer than the old connection and there is no increase in hazard to the customer. As compared with transformers that have no protection it gives very much better protection to the customer because it prevents high voltage from entering into the customer's circuits and the hazard from fire or personal injury is very much greater due to the high-voltage power current than to any surge that is likely to pass through into the customer's circuits.

A. S. Brookes: In reference to the paper by Messrs. Harding and Sprague, I should like to ask what type lightning arresters they used in their tests, what voltages they measured across the arresters and the value of the arrester current.

Their method of testing requires considerable analysis to determine whether and if it simulates the condition of direct strokes. It seems to be the reverse of the induced surge which, according to the accepted theory, is drawn up on the conductors slowly and then released by the discharge of the cloud. I feel that some actual oscillograms would assist greatly in showing just how their method duplicates actual conditions.

In one of their conclusions, they state that a well grounded, secondary neutral wire acts to reduce induced potentials on adjacent wires. A time element enters in here and it should be noticed that this protection is only fully effective when the ground connection is very near the point under consideration. When the ground is an appreciable distance away and the lightning surge has a steep front, flashover of the transformer bushing may occur before a charge can be drawn up on the secondary neutral. In other words, secondary neutral grounds are most effective in protecting the secondary windings from induced surges when placed on the pole adjacent to the transformer pole.

The paper states that high voltages appeared across the secondary windings of the transformer. While we did not measure this potential directly, we did find very little difference was caused in service voltages by removing the low-voltage arresters which were across the secondary of the transformer.

The statement about a non-inductive load in the consumer's premises reducing the service potentials might be amplified. The magnitude of this effect can be computed if the resistance of the load and surge impedance of the service wires are known. I should like to ask the authors if they calculated any checks on the measured values. Actually, it would seem that the branching of the house wiring at the meter board would reduce the voltage at that point very considerably, and particularly so if the wiring was enclosed in *BX*. This is more dependable protection than turning on the lamps during a thunderstorm and considerably safer. The possibility of a surge entering at the same time a consumer turns on a lamp is small but it does exist, and the practise is not to be recommended.

When using the interconnection, a surge on the primary causes almost equal current to flow in each of the three secondary wires. Hence, the voltage difference between the wires is small. The potential difference appears at points where the current in the secondary neutral is drained off by a ground connection. This voltage appears on the consumers' premises with the present construction in the case of a lightning outage and causes no trouble. This voltage can be partially drained off by low-voltage arresters connecting the secondary phase wires to the neutral ground at some pole other than the one the transformer is on. However, the gain probably does not warrant the expense. The interconnection produces essentially the same voltages at the service entrance as are experienced at present with a flashover, and higher potentials than at present with surges which cause arrester breakdown but no flashover.

In the conclusions, the authors give figures on the reduction of voltages at the transformer by the use of the interconnection with various ground resistances. While they do not give directly the effect of the interconnection on the voltages in which we are interested, those across the transformer bushings, we would expect a reduction here irrespective of the primary arrester and secondary neutral ground resistances. This is true because the secondary neutral will drain off part of the current, raising the secondary potential but decreasing the voltage difference across the transformer bushings. In other words, the interconnection will improve voltage conditions at the transformer, whether or not they are so bad that flashovers are anticipated.

The analysis could have been made considerably more valuable by a more detailed consideration of the circuit distances involved, and if more data on the surge current and the circuit details were given. I feel that the interconnection of the primary arrester ground and the secondary neutral has more merits than the results given in this paper indicate.

J. K. Hodnette: The primary requirements for the protection of distribution systems against lightning are:

1. The protection of the connected apparatus against damage from excessive voltage stress.
2. The prevention of circuit outages or interruptions.
3. The protection of secondary service circuits against voltages which might be hazardous to life or secondary apparatus.

The papers of this symposium on distribution circuit protection indicate that the protection to distribution transformers afforded by lightning arresters connected in the usual manner may be inadequate, although arresters at the present time are developed to a high state of perfection. This is due to conditions over which no direct control is possible, such as ground resistance, length of lightning arrester ground connection, etc. Effective protection requires the elimination of these factors, and the authors propose as a solution the interconnection of primary arrester ground and secondary neutral. That this connection produces no additional hazard in the secondary service lines over what exists under the present conditions is confirmed by both experience and laboratory tests.

These facts are of great interest from the standpoint of the design of distribution transformers. The establishment of a definite value for the surge stress permits a more accurate design of the transformer insulation, and suggests the possibility of a self-contained self-protecting transformer. The Westinghouse Company has already developed a distribution transformer which successfully fulfills all of the requirements for a surge-proof transformer. It is self-protecting against surge voltages and requires no external protective apparatus of any kind. It is outage-proof from lightning disturbances. The secondary is fully as safe against abnormal voltages as existing transformers. This transformer is a unit apparatus within which means are provided for protecting it against surge voltages. Surge discharge devices are placed inside the transformer tank and connected between each winding and the tank and core in such a way that the voltage stress that can exist between the high-voltage and low-voltage windings and between these windings and the core

and case, is definitely limited in magnitude. In this manner a voltage stress higher than a predetermined safe value cannot exist upon any part of the transformer insulation, and therefore complete and positive protection of the transformer is assured.

The devices used for obtaining these results are deion surge protective gaps. These devices operate on the well-known deion principle. That is, after a surge is discharged, the arc path is deionized and normal voltage restored.

In operation, when a surge potential exists on the primary terminal of sufficient magnitude to cause any damage to the insulation, the device connected to the high-voltage lead limits the stress that can exist upon the high-voltage insulation by flashing over to the tank. Likewise the device connected to the low-voltage winding flashes over and discharges the surge to ground through the secondary neutral. If the neutral is not grounded, a similar low-voltage device conducts the surge from the case directly to ground. By incorporating in the protective gaps a small series resistor, the dynamic voltage is restored without causing the primary fuse to blow or a relay operation to take place with its consequent interruption of the feeder circuit.

Many laboratory tests have been made to prove the value of this surge-proof construction. Conditions as nearly representing service conditions as possible were employed, and surges of various magnitudes up to 1,500,000 volts have been repeatedly impressed upon the excited supply lines. In every case the transformer was protected and normal voltage restored without so much as causing a flicker in secondary lamp leads.

The interconnection of the primary lightning arrester ground and the secondary neutral as recommended by this symposium as the means for securing adequate protection for distribution transformers possibly constitutes an infringement of the National Electrical Code. By providing a circuit for the surge current directly from the case to earth, the surge-proof transformer is self-protecting from surges entering both primary and secondary circuits and does not violate the letter or spirit of the Code.

H. V. Putman: Mr. Roper brought out a point of significance in the fact that the great majority of transformer troubles from lightning occur in the smaller sized transformers where small bushings and close clearances are used. His company has discontinued the use of the smaller sizes on this account, but he strongly recommended larger bushings and more generous clearances. Manufacturers would do well to heed Mr. Roper's criticism, which is well founded on actual operating experience.

Another important point relating to the grounding of distribution tanks was brought out by Mr. Dean. The entire industry will do well to ponder carefully this whole subject of grounding tanks.

With the question of grounding tanks in the picture, the interconnection appears to lose one of its important advantages. The several authors generally agreed that connecting the lightning arrester ground connection to the low-voltage neutral would result in greatly improved protection to transformers. This has been demonstrated in certain particular applications, having isolated tanks and low resistance customer's grounds. While this connection discharges all surges to ground through the customer's ground connection, it was generally agreed that this could be done safely so long as the customer's ground was a water pipe connection of low resistance. It appeared to be the general opinion that if a modification of the National Electrical Code is necessary to permit the use of this interconnection, it should be made.

In considering this matter, the straight interconnection appears to have certain limitations which ought to be given careful consideration. With an isolated tank, the interconnection does give protection entirely independent of the ground resistance, but when the tank is grounded, the protection which the interconnection gives the transformer depends on the customer's ground resistance and the length of the service line or ground connection relative to the steepness of the front of the surge. This has been the source of difficulty with the conventional lightning arrester protection. The same difficulty is present with the interconnection when a grounded tank is used.

If there is no ground on the secondary service, as is usually the case in star delta connected transformers, for supplying three-phase power, then the use of the interconnection is undesirable for two reasons: First, it would pass on to the customer's apparatus the surges coming in over the high-voltage lines; and second, the grounding of tanks under these conditions would destroy the protection afforded by the interconnection completely. The reason for this is easy to understand. Suppose a surge of 100 kv. enters the transformer. The high-voltage winding is raised to this potential. If the lightning arrester discharge voltage is 15 kv., the low-voltage winding will reach a potential of 85 kv., since the surge impedance of the low-voltage service lines and the three-phase connected apparatus is likely to be very high. The potential of the tank and core may start to rise, but will be restored to ground quickly within a fraction of a microsecond, so that a difference of potential of 85 kv. would exist across the insulation between the low-voltage winding and ground, and this would be of sufficient magnitude to cause failure.

It appears, therefore, that the straight interconnection is not well adapted to installations having a low-voltage neutral ground connection of high resistance, nor to installations having no ground connection on the service lines, nor to installations having grounded tanks, nor to three-phase installations.

There seems to be an impression in some quarters that only by the use of the interconnection can effective transformer protection be secured. But this is not the case. The use of a grounded tank with lightning arresters connected between the tank and the high-voltage lines, and a coordinating gap to protect the low-voltage winding against surges entering on the service lines, affords a method of protection which is effective under all conditions, which is universal in its application, which conducts surges directly to ground instead of into the customer's neutral, which appears to be safer to the lineman and the public than the present equipment, with conventional lightning arrester protection, and which raises no question of a possible Code violation.

M. G. Lloyd: In drawing conclusions from these papers, it is necessary to exercise considerable caution. In some particulars these papers present contradictory results, and in one or two cases the conclusions of the authors do not appear to be justified by their observations.

The subject is of particular interest because of the prevalence of transformer failures. Conditions in this respect appear to be improving with better transformer construction and better performance of lightning arresters. It is clearly shown, however, that lightning arresters give very uncertain protection when the impedance to ground is high. Thus, better protection can be secured in a district such as Chicago, where resistances to ground are comparatively low as contrasted with Boston, where resistances to ground are typically high. In the Philadelphia district, good results have been obtained by efforts to keep the ground resistance low.

A proposal to connect the ground lead of a primary lightning arrester to the secondary neutral has had attention from most of the authors of these papers. This practise appears unobjectionable if it does not increase the potential to ground of the secondary conductors. This is a point that requires careful analysis.

Harding and Sprague conclude that no extra hazard is introduced. McEachron and Saxon found that the voltage surge on the secondary was limited to 400 volts when the primary arrester had a resistance to ground of 10 ohms. With interconnection between the primary arrester and the secondary neutral, however, it was found that the secondary arced over (3,900 volts).

Opsahl, Brookes and Southgate found that interconnection produces no higher voltages on the secondary than are obtained without such interconnection if the flashover occurs on the pri-

mary. The surge value, however, was definitely affected by the resistance to ground and the secondary voltage was doubled if the ground on the primary arrester was altogether removed.

The Philadelphia Electric Company found no bad effects from the interconnection, but it should be noted that interconnection in that case was definitely limited to locations where there was a low secondary resistance to ground and with connections to ground on the premises of not less than ten customers.

Good results are generally reported to result from the interconnection between the primary arrester and the secondary grounded neutral, and it is to be expected on theoretical grounds that such a connection would limit the voltage difference between the primary and secondary coils of the transformer and thus be effective in preventing flashovers and breakdowns of insulation. It is necessary to examine rather carefully, however, whether the good results reported from the field are due solely to such interconnection. The reports here seem to be somewhat conflicting.

Harding and Sprague found that the potential differences measured at the transformer depended very decidedly upon resistance to ground. When this resistance was low for both the primary arrester and the secondary neutral, interconnection had no effect upon the measured potential. Similarly, when both resistances were high there was no measured effect. When the resistance of the secondary neutral ground was high and the resistance of the ground of the primary arrester was low, interconnection produced an increase in the measured potential. The only case for which they found a reduction in the effect was when the secondary neutral ground had a low resistance and the primary arrester ground a high resistance.

Dambly, Ekvall and Phelps found that interconnection had no effect upon the trouble experienced in the field.

McEachron and Saxon found that the interconnection protected the transformer in all cases, whereas without the interconnection a high resistance of the primary arrester ground may prevent the protection of the transformer. Fig. 4 in their paper shows that the secondary potential was definitely raised by the interconnection when the resistance to ground was 60 ohms. It is regrettable that no similar results are given for a resistance of 10 ohms, which would correspond to the conditions in Fig. 2. The primary potential in both Figs. 3 and 4 was raised by the higher resistance. Similar curves would be of great interest to show what takes place when different values of resistance are interposed in the interconnection.

Interconnection appears to be practically equivalent to a very good connection to ground, on both the secondary neutral and the primary arrester. If the good results can be obtained by such separate grounds, it would seem to have advantages over a direct interconnection. The real problem appears to lie with situations where good grounds are not easily obtained. The authors of three of these papers advocate interconnection when the secondaries are well grounded. The converse proposition would seem to be that interconnection is not desirable where only driven grounds of high resistance are available. Mr. Roper states that the cost necessary to bring resistance to ground below 50 ohms is not warranted by the results obtained.

In studying this problem, it would seem necessary to separate the rural problem from the city problem. In cities, water-pipe grounds are usually available for the secondary circuits entering customers' premises, and the best grounds for the primary arresters can probably be obtained by an interconnection with the secondary neutral. For this practise to be safe, it should be carried out only when there is a multiplicity of grounds on the secondary neutral. Mr. Roper points out the value of interconnecting the secondary neutrals on different transformers even where a secondary network system is not used.

The real problem arises in rural communities where water-pipe grounds are not available and effective grounding is a difficult condition to obtain. Even McEachron and Saxon admit that interconnection under these conditions increases the hazard.

The Committee on Protection Against Lightning of the National Fire Protection Association has had under consideration for some time the advisability of using lightning arresters on overhead secondary circuits where they enter buildings. The fire hazard arising from lightning surges coming in to buildings over such wires is well recognized, and fires have often occurred in this way. Messrs. Opsahl, Brookes and Southgate, in their paper, and Dr. Fortescue, in his discussion, have indicated that such a practise may be desirable. It would seem to be necessary only in rural districts and only where the wires enter the building as separate open wires. Where they are run in conduit the latter would be grounded and would automatically act as a lightning arrester since a surge would probably jump from the conductor to the conduit. For open wires an arrester would seem necessary, but one of cheap construction would suffice for the purpose, since it would be necessary to interrupt follow current at only 120 volts. Experiments with the type of arrester used on radio antennas indicate that a slight modification would make such arresters effective for this purpose.

Edward Beck: The papers indicate rather definitely that in the present state of the art, the principal factors that enter into the protection of a distribution transformer are, outside of the construction of the transformer itself, the primary arrester ground lead and ground resistance. Interconnection of the primary lightning arrester ground terminal with the secondary neutral wire eliminates these variables because it limits the potential differences around the transformer itself to the lightning arrester voltage. Because of the favorable protective results which this interconnection promises, it becomes important to secure some idea of what will occur in the secondary circuits if the interconnection is used, thereby directing surges which may occur on the primary into the secondary neutral.

In order to investigate this, a circuit was set up in the laboratory to simulate an energized 2,300-volt circuit feeding a 110/220-volt house circuit. The house circuit was connected to various common appliances by which the transformer could be loaded to its capacity.

Surges were impressed on the primary from a surge generator, of magnitudes sufficient to discharge 800, 1,600, 3,000 amperes through the primary arresters. The primary arresters were 3,000-volt autovalve arresters of the latest type. Various values of house ground resistances were used, varying from zero to 57 ohms. Tests were made with one side of the primary grounded and ungrounded. Cathode ray oscillograms were made of the voltages occurring between each secondary wire and true ground. Measurements were also made of the potential differences occurring between the secondary phase wires and neutral.

One of the chief things of interest, is the voltages which may occur between the secondary phase wires and neutral, as these may produce flashovers in sockets or appliances. It was found by cathode ray oscillograph measurements that the voltages to ground of the phase wires and the neutral wire are very nearly alike except at the first instant. This potential difference may be due to induction through the transformer before the arrester discharges or it may be due to the release of a steep wave by the arrester discharge. The break down of the arrester releases a very steep surge into the secondary circuit which by reflection produces momentary high differences of potential between the secondary phase and neutral wires. In this test set-up crest voltages of 8 to 10 kv. were measured by means of a sphere gap. No appreciable variation occurred in this voltage between phase and neutral with "house" ground resistances varying from 0—57 ohms. These voltages can be reduced to negligible values by the use of 110-volt lightning arresters or small capacitors between phase wire and neutral at the house entrance. Their use is not considered essential, in the usual house circuit where the neutral is grounded and attachment plugs, etc., provide discharge paths between phase and neutral. Where the secondary circuits are ungrounded or highly insulated throughout, such as may be the

case in electric range circuits, protective devices at the house entrance may be of considerable benefit, for instance, in the prevention of damage to ranges. It is to be noted that this is no worse a condition than will exist with the present usual methods of protection when the transformer flashes over. Tests were made with various loads on the secondary circuit varying from zero to full load, that is, 5 kva. The load consisted of the various appliances and lamps mentioned in the figure. It was found that flashovers would occur in lamp sockets and attachment plugs to a considerable degree. These flashovers were rarely followed by a power arc. Consequently few outages resulted. Tests were made with the appliances on the circuit and the radio set in operation and it was found that operation went on normally when the primary was surged although flashovers occurred in the secondary circuit. There was one exception which was a rather old socket which flashed over several times and finally produced a short circuit blowing a low-voltage fuse. A few flashovers occurred on the terminal board of the watthour meter, but the watthour meter was not damaged in any of the tests made.

During the tests well over 1,000 surges were impressed on the same distribution transformer protected by the same lightning arrester feeding the same house circuit. In a particular group of tests, there were three interruptions to the customer's service in about 1,000 operations. These interruptions consisting of blown fuses, one of these three cases necessitated replacement of a lamp socket.

Later, a failure of a toaster occurred. It had been hot for sometime, and had been subjected to over 1,000 surges. The frame of the toaster happened to be grounded to true ground. Several flashovers took place in the attachment plug which was already hot from the heat of the toaster. It developed a short circuit.

The voltages which may exist from all of the secondary wires to the earth will be the IR drop across the house ground resistance. It was found that these can be reduced by use of an auxiliary protective gap between the secondary neutral wire and ground at or near the transformer. Tests were made with such a gap in the circuit in series with a resistor to simulate the ground resistance of the driven ground at the transformer pole. This resistance was varied from zero to about 50 ohms and it was found that a considerable reduction in voltage between the house circuits and true earth was secured when the house ground is of some resistance.

During these tests, the lightning arrester was connected behind the primary fused cutouts. This is rather contrary to past practise but presents several advantages. It was found that satisfactory operation was obtained with primary fuse links as small as 5 amperes, and that a 3-ampere fuse link would pass surge currents at intervals of about a minute without blowing, but would rupture on rapidly applied surges.

These data are being presented as information. The improved protection given the transformer by the interconnection is probably admitted by everyone. Regarding the disturbances in the secondary, it is undoubtedly true that the interconnection can make conditions no worse in the secondary than they already are, and apparently they are not bad.

J. J. Torok: The majority of the lightning papers deal principally with the protection of the transformer. In reviewing the subject I was at first somewhat concerned by the hazards that the present systems might have to the consumer or customer. Statistics, some of which are being presented in these papers, show quite conclusively that the hazard to the customer under the present system is very small. A comparison of the two systems shows that the proposed system is far less hazardous. I have arrived at this conclusion in the following manner.

Let us assume that on a pole there is a step-down transformer, the primary of which is 2,200 volts or higher and the secondary is the common three-wire type, the central lead of which is always grounded on or near the customer's property. We will consider then that the consumer during a lightning storm may be in contact with some electrical device and an independent ground of his own. The household equipment usually is of fairly low insulation, consequently, any high voltage may easily flashover to the handle which is in the hands of the customer. With these connections we can now consider the different conditions with respect to the safety of the user.

The small amount of research that has been conducted by the high-voltage laboratories shows quite definitely that impulse voltages are not very dangerous even for high voltages and large currents. Experiments made on rodents and an occasional accidental one on humans show that impulses of such magnitudes as 200,000 volts and several hundred amperes are not as dangerous as 2,200 volts 60 cycles. This is obvious when we consider the time of application of the two voltages, the impulse lasts but a very short time, in fact 30 or 40 millionths of a second, whereas the 60 cycle can last as long as the circuit is complete. It also follows that the shorter the application of the 60 cycle the less dangerous it is. We all know how harmless static gathered from the carpet is, and this may be at potentials of the order of 10,000 volts and that 2,200 volts 60 cycles is used on the electric chair.

Impulse voltages which may appear at the terminals of a transformer may vary in magnitude from a very low value to a very high value. The distribution of these voltage waves with respect

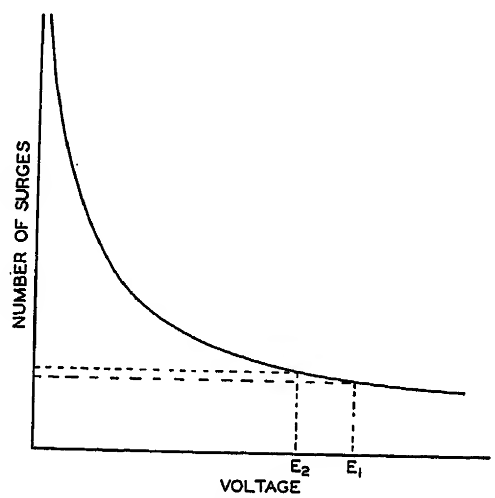

Fig. 1

to magnitude is of the nature shown in Fig. 1. The shape of this curve for various insulations is very similar. The position with respect to voltage, however, is dependent chiefly upon the insulation of the line. Let us assume on this curve that magnitudes of voltages appearing at this point above the specified value E_1 will cause flashover of the bushings of the transformer. Voltages above this value will flash over the bushings of the primary, raise the potential of the case to a high value, and thus cause flashover to the secondary leads. Since arcs in open air are difficult to extinguish it is very likely that this flashover will establish a 60-cycle arc then power current will flow from the primary circuit into the secondary leads and from there to ground through the customer's service. The potential to which the secondary lead will rise will depend upon two factors; (1) the short-circuit currents in the primary circuit, and (2) the resistance of the secondary ground. Since the customer may be connected to an independent ground he will receive not only the voltage drop of the transformer but also the voltage drop across the ground. From this standpoint one can see that it is possible to obtain 60-cycle potential from 110 volts to 2,200 (assuming of course that the primary circuit voltage is 2,200). This 60-cycle voltage will appear on the secondary circuit as long as the arc is maintained across the transformer terminals, perhaps it may be limited by a

fuse or by a group of network switches. Generally this period of time may be anywhere from one-half cycle up to several seconds. Such is the present condition.

If, however, we consider the system in which the protective devices are interconnected between the primary and the secondary neutral we will have an entirely different condition wherein these hazards do not appear. Going back to our distribution curve of impulse voltage we find that the action of the arresters comes in at a lower voltage than did the flashover of the bushings but this increase in number of surges that pass on to the secondary is very small. These, as has already been stated, are not very dangerous. On the other hand, due to the action of the arresters there is no 60-cycle power follow or at least if it does, only for a half-cycle, but no longer. The arrester will either cut off at a value above the 60-cycle voltage so that no 60 cycle follows, or at the end of the first half cycle. After that the primary and secondary are again isolated. Under this condition the maximum period of time at which high voltage may appear upon the secondary circuit is one one-hundred-twentieth of a second.

Comparing the two systems again we find that in the present system it is possible to have very high 60-cycle voltages on the customer's leads for several seconds. In the proposed interconnection the maximum period of time that is possible is one one-hundred-twentieth of a second, generally less. From these two conditions it is quite obvious that the second system is much safer than the first.

K. B. McEachron: All of the papers mention the use of the interconnection of the primary arrester ground and the grounded secondary neutral. The papers dealing with the field investigations all agree that better protection to the transformer will be had with the interconnection than now exists without it.

Interconnection has been in practise in several locations for a period of years with most satisfactory results. In these cases the conventional lightning arrester has been used, the arrester ground being tied into the secondary neutral. However, test data are now available which indicate that where multiple low resistance grounds, as with water-pipe grounds, exist, the ground at the arrester can be eliminated if desired. As soon as this is done a material reduction in the cost of protection is realized, and it becomes possible to incorporate the arrester protection inside of the transformer tank so that it becomes a complete self-contained unit.

In considering how this might best be done, the only design of which I am aware, in which this idea of protection within the transformer, coupled with interconnection, was used, was given careful study. I refer to a scheme used in Boston several years ago which was patented in 1919* and with improvements in 1923.† This protection scheme which was developed in Pittsfield consisted of gaps in each primary bushing to the case with an additional gap between the case and the grounded secondary neutral.

A considerable experience was built up with this arrangement in Boston, but it had certain disadvantages, some of which were of sufficient importance to result in its discontinuance. Those disadvantages were not dependent on the idea of interconnection, but were the result of the method of protection used and its application.

This early scheme of using gaps and making the transformer case a part of the circuit without permanently grounding the case gives rise to certain sources of trouble, as follows:

1. The gaps were connected from primary to secondary neutral without a high resistance or its equivalent in the circuit to limit the flow of follow current. When the interconnection is made without the use of the usual form of lightning arrester which has the ability to limit the flow of follow current to small magnitude for one-half cycle, the arc once established will not interrupt itself. This means that the power currents which flow into the secondary system are limited only by the impedance of the secondary ground in series with the impedance of the line. This may constitute a serious hazard in those cases where separate grounds are found in the same building.

It may be argued that the same conditions exist when bushings flash over. When both a primary and a secondary bushing arc over, the same condition does occur, but when protected by the conventional form of arrester properly applied, a bushing flashover seldom occurs, and thus the number of accidental primary-secondary contacts is kept to a small value. If now the arrester is replaced by the interconnected gaps, every operation causes a primary-secondary contact. Where all grounds in a building are not tied together an increased hazard is likely to result from such a use of direct primary-secondary connection.

2. Using the tank as a part of the circuit does not give the degree of safety to a lineman that either solidly grounding the tank or completely insulating it would give. The safety of the lineman may depend upon the integrity of the gap insulation whose strength is much less than that of the bushings. After a period of years such gaps may leak sufficiently so that the tank may take either the primary or the secondary potential. Furthermore, during periods of discharge, dangerous potentials on the tank may become a source of hazard.

3. A necessary part of the use of the gaps is some method of interrupting the flow of follow current following a lightning discharge. The primary fuse served in this capacity, and as a result, the number of fuse blowings was considerably increased over that experienced with the use of the conventional arrester. Today, with increased stress on reliability, any increase in fuse blowing is obviously a step in the wrong direction.

Having had this background of experience with gaps and remembering the good results obtained by those who have used the conventional arrester with interconnection, the best method of obtaining the advantages of interconnection in the self-contained unit appears to be the incorporation of the standard arrester within the transformer.

The experience of those operating companies who have used the interconnection with the conventional arrester has been very good indeed. To apply the scheme generally and to secure the best protection required that the arrester and the transformer be mounted on the same pole, which has not always been past practise. Further, in line with the general effort to reduce costs of installation and reduce the congestion on poles, it appears highly desirable to provide a reliable form of protection which can be placed inside the transformer tank without making the tank a part of the circuit.

In considering what form this arrester should take, certain requirements as to space have to be met, which have not been required of the arrester mounted external to the transformer. Careful study of all of the factors involved indicated the advisability of using the conventional form of arrester which has had much field experience, but so modifying it constructionally that it would fit within the space available without making any change in the existing transformer tank. How this has been accomplished may be seen from Fig. 2 which shows two arresters designed for operation with a 4,600-volt circuit. The transformer shown is rated 1.5 kva. 2,400/4,800/8,320 Y-120/240 volts.

The arresters shown are of the Thyrite type and completely sealed within a porcelain container. With this construction the arrester operation is in no way different than when applied externally, and has the same factors of safety and the same reliability.

With any modern arrester connected inside the primary fuses the lightning discharge currents will pass through the fuses and may blow fuses below 5 ampere rating in case of extremely severe discharges. Although this tends to increase fuse blowing in the small sizes, its effect is counteracted by a great reduction in the number of bushing flashovers which also result in blown fuses.

*U. S. Patent, L. R. Brown, No. 1,310,054.

†U. S. Patent, C. H. Kline, No. 1,462,346.

The paper by Harding and Sprague presents valuable data concerning potentials which may be induced on different conductors. In analyzing their results, however, it must be remembered that the voltages were small and consequently the current in the conductors and through the arrester was small, which does not give rise to the significant differences resulting from ground resistance which were obtained in the McEachron-Saxon paper. A statement from the authors of the amount of current would be of value when considering the effects of grounds. On page 236 the statement is made that the voltages across the secondary coils were approximately 20 to 80 per cent of those existing across the primary windings. I wonder if Mr. Roper has any data to show that the power banks are more susceptible in the secondary windings than in the primary. Perhaps secondary protection would be justified in such cases.

On page 236 of the Harding and Sprague paper the statement is made that the effect of the interconnection is dependent on such factors as the steepness of the wave and the time lag of the arresters, and hence no definite statement can be made that the connection is always beneficial. With the interconnection the potential between the secondary neutral and the primary terminal will not exceed the potential allowed by the arrester which, if it has time lag, depends on the rate of potential rise. With the conventional connection the arrester has a ground lead of considerable length and some ground resistance, so the voltage with interconnection will always be less than without it, without regard to wave front. Currents of considerable magnitude are necessary to bring out the effect of ground resistance clearly.

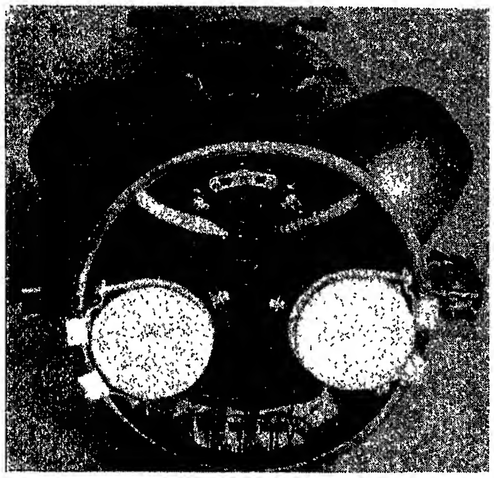

Fig. 2

Concerning conclusion 8 of the Harding and Sprague paper, the potential between the primary winding and secondary winding is not particularly dependent on the resistance between the secondary neutral and the ground, nor the resistance of the arrester ground if the interconnection is used. The arrester operates on difference of potential across its terminals, and its potential drop will not be less with good grounds than with poor grounds. The principle involved in interconnection is the equalization of potential between the primary and the secondary, and this is dependent on the arrester ground or the secondary neutral ground only as these affect the rate of voltage rise across the arrester and the rate of rise and value of current through the arrester. The potentials found on the secondary network are very dependent on the resistances to ground over which the discharge passes, but the maximum potential differences in the transformer are not dependent on the grounds but on the arrester when interconnection is practised.

The data contained in the three papers dealing with operating experience present a wealth of worth while material. I disagree with suggestion 4 of Mr. Roper's paper. While a second ground may be justified, there seems to be no justification for the second ground wire down the pole. It would be interesting if Mr. Roper would give the basis for this suggestion. I would like also to have Mr. Roper give further explanation of just what he means by suggestion 10, and the basis for such a suggestion.

The paper by Messrs. Haines and Corney is interesting because of the comparison of transformer failure with and without arresters. The results of Table I show a considerable reduction in failures even with an average ground resistance of 201 ohms. However, the statement in conclusion 3 seems to indicate that further improvement from the ground resistance standpoint will only come with resistances of 100 ohms or less. While no conclusion can be drawn, it is perhaps worth while to calculate the arrester currents for the induced case and for the direct stroke making certain assumptions. Assuming that the strength of the transformer in service can be taken as 65 kv. and assuming that the arrester potential is 15 kv., then with a ground resistance of 201 ohms the induced voltage on the line would have been 190 kv. (traveling wave 95 kv.) using a surge impedance of 500 ohms and the assumption of instantaneous cloud discharge. If 190 kv. is taken as the maximum traveling wave potential which the line can hold without flashover to ground, it can easily be shown that a ground resistance in excess of 80 ohms would not give protection. Because of varying rates of cloud discharge these two forms of discharge undoubtedly merge into each other, but it is interesting to note a potential of 190 kv. is not far from the probable maximum that such circuits could hold without spilling over.

The experience in Philadelphia, as reported by Dambly, Ekvall and Phelps is particularly interesting in view of the experience with arresters in Boston, as both have high resistance grounds. It is in communities where good grounds are hard to obtain that the benefits of interconnection will be most pronounced. It is gratifying to note the good results thus far obtained in Philadelphia. The data contained in Table III, and in Fig. 7 are of much value in showing the classification troubles and what it means in customer hours of interruption. It is with such data that it becomes possible to evaluate properly the benefits to be gained from lightning protection. The number of transformer troubles alone does not give the complete picture as an economic problem. It would be of value if the authors could also give the number of power follows taking place between conductors and conductors and grounded objects.

A. M. Opsahl: Mr. McEachron mentions the fact that he obtained secondary circuit flashovers when surges were applied to the transformer with various connections. He does not state whether these secondary flashovers resulted in a power arc or a secondary fuse burn-out when power voltage was also applied to the primary of the transformer. I do not think that power would follow and I should like to know whether or not it did in his tests.

In his presentation Mr. Roper showed a slide of the various factors that were discussed in his study of the variables that entered into the failure of distribution transformers. I should like to see a record of these variable factors and the conclusion that he has drawn as to their relative importance in the failure of distribution transformers. Mr. Roper states that about 40 failures of watt-hour meters occur per year due to lightning. It seems to me that there is a probability of several meters failing due to a surge into the secondary with power, whenever a transformer flashes over and burns out or blows a primary fuse. What coordination is there between the meter failures and the transformer failures, or fuse blowings?

Mr. Roper implies that ground resistance has no effect on the protection up to a ground resistance of 50 ohms in the primary arrester ground. Assume a 50-ohm ground and a 1,000-ampere surge current. This would result in 50 kilovolts added to the arrester characteristics for the total voltage appearing across the primary bushings due to arrester and ground resistance alone.

It seems inconsistent that there should be such a small difference in the failures where the ground resistance is low, in the order of a few ohms and where it is in the order of 50 ohms.

I ask Mr. Roper what experience he has had with the parallel ground leads which he mentioned. As I understood Mr. Roper, he has obtained permission from the Illinois Commission to install certain transformers with the interconnections. I assume from this that he has no service experience on this connection to date. From his 20 years investigation of distribution transformer protection, I also ask Mr. Roper what his opinion is as to the hazards to the customer where the proposed interconnection is used.

Mr. Corney does not state what ground resistances can be attained at the customers' premises under the conditions in his territory. He does not state where the transformer flashovers occur but I presume it is over the bushing and into the secondary neutral. Under such conditions, what hazard is there to the customers or what troubles do they experience in the secondary circuit?

R. E. Jones: The interconnection of arrester ground and secondary neutral as described by Mr. McEachron has been common practise in Ontario for many years with the addition that usually primary neutral and transformer case are also tied to the same ground. The results have been very satisfactory under above described conditions.

However in a number of installations on rural lines where the primary neutral was not tied to the secondary neutral the arrester has broken down without destroying itself and allowed power current to flow through the driven rod of the secondary ground without blowing the substation fuse. This ground was gradually dried out and the resulting high resistance caused the current to flow to ground through the consumers' premises damaging radio equipment and motors.

F. W. Gay: It should be possible to obtain additional protection against transformer failure by introducing capacity in shunt between each high-voltage terminal and tank and between each low-voltage terminal and tank. Such capacity having low surge impedance to waves of relatively short duration will tend to maintain all windings and tank at substantially the same potential.

This result can be easily obtained by passing both primary and secondary leads into the transformer through metal clad cables. The metal covering of the cables must be solidly grounded to the transformer tank. Each such cable should include within the metal sheath an oil stop joint so that the continuity of the solid insulation need not be broken from coil to line wire.

Herman Halperin: On page 260 of the paper by Messrs. Haines and Corney it is stated that there is no lightning protection for 3,400 overhead transformers installed in certain areas in and closely adjacent to the City of Boston. What were the rates of burnouts and fuse blowings for these transformers due to lightning?

H. N. Ekvall: The paper by Mr. D. W. Roper covers the results of extensive investigations of many factors associated with the problem of distribution system lightning protection. For many of these factors, the Philadelphia Electric Company through investigations on its systems, has obtained comparable results. There is, however, considerable difference in the methods used in determining arrester performance.

A comparison of the methods of analysis used by the Commonwealth Edison Company in the study of its 4,000-volt grounded three-phase system with those of the Philadelphia Electric Company on its 2,300-volt ungrounded two-phase system follows:

In Chicago, arresters have been installed at practically every transformer. Under these conditions, performance can be determined only from the average rate of trouble over a period of years, before and after installing arresters. In Philadelphia, arresters have been installed on only part of the transformers. Their distribution throughout the entire area makes it possible to study performance by comparing the rate of trouble on protected and unprotected transformers for any one year.

With the Chicago setup, the wide variation in lightning severity for the various lightning seasons may lead to erroneous conclusions. It is believed, however, under conditions such as exist in Philadelphia, the variations in lightning severity are compensated for, since protected and unprotected transformers are exposed to essentially the same storm conditions. Experience indicates this to be very nearly the case since arrester performance or the reduction in trouble by arresters has been fairly uniform over the past five years. During this period the average density of arresters varied from 25 to 50 per cent indicating that there was a continuous change in arrester distribution, thereby permitting performance to be studied on various groups of transformers.

Another factor of importance to arrester performance is transformer size. This is apparent from the large difference in rate of trouble on the various sizes. The Commonwealth Edison Company attempted to eliminate the effect of transformer size by dividing its territory into small areas having approximately the same distribution of transformer sizes in each. Only one type of arrester was installed in a given area, the various types being assigned to areas which would permit the best distribution over the territory. The Philadelphia Electric Company did not try to eliminate the effect of transformer size but accounted for it by obtaining the rate of trouble on various size groups of protected and unprotected transformers. The performance obtained in this way showed very little reduction in trouble by use of arresters on the small transformers and considerable reduction on the large transformers. If the performance of arresters is determined without considering transformer size, the results may not accurately indicate the relative effectiveness of arresters of different types.

F. E. Andrews and E. R. Hendrickson: We believe that the method which Messrs. Dambly, Ekvall and Phelps have used of comparing interruptions by customer hours is a step somewhat in advance of classifications made on the basis of the number of interruptions. It should, however, be pointed out that in many cases customer hours do not give an adequate picture of the relative seriousness of interruptions.

As a means of obtaining a better picture of this factor, it is suggested that some consideration might properly be given to the addition of the kva. of connected transformer capacity which has been interrupted, thus obtaining a factor which takes into consideration the number of customers, the length of interruption, and the amount of connected load interrupted.

From the tabulation in Fig. 7 it is noted that the largest single cause of interruptions is due to aerial distribution wire having caused 30 per cent of the total customer hour interruptions. Of this, 76 per cent is listed as having occurred during electric storms due to causes unknown. Analyses which have been made of such interruptions of the distribution system of the Public Service Company of Northern Illinois indicate that there is some reason to believe that a number of these may be due to flashovers started by lightning and followed up by the 60-cycle power arc. Investigations have been made of a number of cases of such failures. Information which has been developed to date is not sufficiently complete to warrant the drawing of definite conclusions. It does, however, indicate the following tendencies:

1. Most cases of phase-to-phase arcing take place when the clearances between phases have been reduced to a value less than normal line spacing. The path to ground is by way of:
    a. An arrester on adjacent phase.
    b. Ground wire on pole.
    c. Anchor guys on pole.
    d. Transmission pole guys passing between phases.
2. Phase-to-phase arcing has been found to have taken place over a distance as great as 16 inches, at 4,000 volts through air.
3. Interruptions to service do not generally occur when location of disturbance is several miles from the substation.

A study which the Public Service Company has made of transformer and fuse troubles has been segregated by voltage and class of territory (rural or urban), but does not include information with respect to the various sizes of transformers as is covered in this report.

For 1930 investigation of transformer and fuse failures indicates that there were twice as many failures in rural territory than in urban, and that the number was considerably higher on the 4,600 and 6,900-volt lines than on the 2,300-volt lines. A summary of this information expressed in per cent of transformers exposed is shown in the following table.

Voltage	Location in service	Failures: Transformer Ltg.	Transformer All	Fuses Ltg.	Fuses All
2,300—Urban	19,592	1.1	2.1	3.9	5.2
2,300—Rural	3,605	3.4	4.3	8.0	9.0
4,600—Rural	417	8.6	8.7	31.1	33.0
6,900—Rural	378	5.5	9.8	25.1	27.8
All voltages in per cent of total locations		1.7	2.6	5.2	6.6

NOTE: The average ground resistance in our territory is somewhat lower than that in the Philadelphia territory, and probably will be in the neighborhood of 50 ohms.

We are particularly interested in the information presented which indicates that arresters were of little or no value on transformers smaller than 15 kva. We believe that this may, to some extent, be due to the higher ground resistance encountered in the Philadelphia territory, thus increasing the voltage to which the transformer is subjected before the arrester becomes operative. This, it appears, would increase the susceptibility of flashovers on the smaller transformers, particularly those of the older type, because of the reduced clearances. A study which has been made of our system in a section of Joliet, Illinois, representing 509 locations over a three-year period, gives results on the value of arresters which are contrary to those drawn in the paper. A summary of these results is given below:

	Arrester ground resistance: 45 ohms and less	45 ohms and up	No arresters	Total
Per cent of total in each group	52.7	21.0	26.3	100
Per cent transformer failures average per year	0.9	1.8	5.4	2.3
Per cent fuse failures average per year	4.4	3.7	7.4	4.9
Per cent transformer and fuse failures average per year	5.3	5.5	12.8	7.2

Although the transformers have not been segregated by size, over 95 per cent of them were smaller than 15 kva. Since there are over twice as many fuse and transformer failures in the locations having no arresters, it is evident that arresters in this case could be justified on transformers smaller than 15 kva. These transformers are all located in the same vicinity so that they receive the same exposure.

C. F. Harding and C. S. Sprague: In reply to the discussion by Mr. Brookes, the primary phase arresters were of a standard make, rated at 3 to 5 kv. as ordinarily used on 2,300-4,000-volt systems. A 300-volt valve type arrester was used on the primary neutral wire. The voltages across the phase arresters were of the order of from 20 to 30 kv. Arrester currents were estimated at a maximum of a few hundred amperes depending upon the ground resistances. No attempt was made to measure these currents since it is difficult to do this without disturbing the circuit.

The larger part of the investigation was performed using voltages induced by an artificial cloud. It has been shown both theoretically and by oscillograms that the induced transients are the same whether the cloud is suddenly discharged or suddenly charged, providing that in the latter case, the cloud potential is maintained constant until the induced transients have disappeared. The induced voltages thus obtained are less severe than the direct discharge of the surge generator into the primaries, since the energy and surge current are less.

A grounded secondary neutral reduces the induced potentials *to ground* on adjacent wires and is most effective in this respect when the ground connection is close to the point under consideration. Potentials to ground on primary wires on the upper arm were reduced 3 to 10 per cent by the secondary neutral. Potentials to ground on the secondary wires adjacent to and on the same arm with the secondary neutral were reduced approximately 30 per cent. However the ground connection causes a difference of potential to appear between secondary wires although the potential to ground of all the secondary wires is reduced. With regard to bushing flashover a steep front surge is less apt to cause flashover when the secondary grounds are remote from the transformer or of high resistance, assuming no interconnection of secondary neutral and arrester ground. The more effective the secondary grounds are in holding the secondaries close to ground potential, the more voltage will be impressed across the transformer, *i. e.*, between primary phase wire and secondaries.

Induced voltages of from 15 to 30 kv. were measured across the three-phase 230-volt windings of the power transformers, having the power secondary ground made to the midpoint of one winding. On the lighting secondary winding the induced voltages from line wires to neutral were of the order of from 4 to 8 kv. There is evidently some neutralizing action occurring in the lighting transformer secondary winding, which action reduces the impedance of the winding to surge currents. The power secondaries and their ground connection present an unbalanced condition to surge currents flowing to ground and it is here if anywhere that our tests have shown the desirability of secondary arresters.

The statement that a non-inductive load in the consumers' premises reduces the voltages at the service entrance by 60 to 70 per cent is based upon measured values. No attempt was made to calculate this effect. It is quite true that as the surge enters the conduit and branches at the cutout box, the voltage is reduced by the lower surge impedance of the conduit system. However, if all lamps are turned off, positive reflections occur at the sockets and due to the short lengths of the wiring circuit, the voltage at the service entrance and at the sockets builds up very quickly to the value obtaining on the secondary wires outside the service. With a non-inductive load on the circuit, the surge current is continually drained off as it enters the service and due to this larger surge current and the regulation of the external circuit, the voltage is considerably reduced at the service entrance and throughout the service. From the standpoint of personal safety there seems to be no reason why one should not turn on the lamps during a thunderstorm. In fact this is very often done, although for the purpose of obtaining light rather than for protection to the house wiring system.

Number 8 of the conclusions presents the effect of the interconnection on the potentials at the transformer with various values of ground resistances. The potentials described as "across the transformer," *i. e.*, between primary phase lead and secondary winding, are those tending to cause bushing flashover. The conclusions reached are derived from tests using induced potentials with relatively low values of surge current flowing after the arrester had broken down.

Since preparing the paper, tests were made using "direct strokes," that is, with the surge generator discharging into each primary wire in turn. In these tests the discharge currents through the arrester were of the order of 2,000 to 3,000 amperes. With the voltage adjusted to a value not quite sufficient to cause bushing flashover the potentials at the transformers were mea-

sured with and without the interconnection and with a variety of ground resistances. The voltages tending to cause flashover were from 50 to 60 kv., without interconnection and from 35 to 38 kv. with interconnection, the latter figure being the maximum voltage across the arrester.

With the voltage raised to a value such that bushing flashover always occurred without interconnection, it was observed that in tained in the Willseyville tests. Grounding the tank with arresters connected to a separate ground allows high stress between primary and tank if ground resistances are high, resulting in primary bushing and lead flashover and consequent fuse blowing. If the windings are stronger than the leads and bushings, substantially all of the interruptions will be due to fuse blowing. With interconnection as shown for the first company tabulated

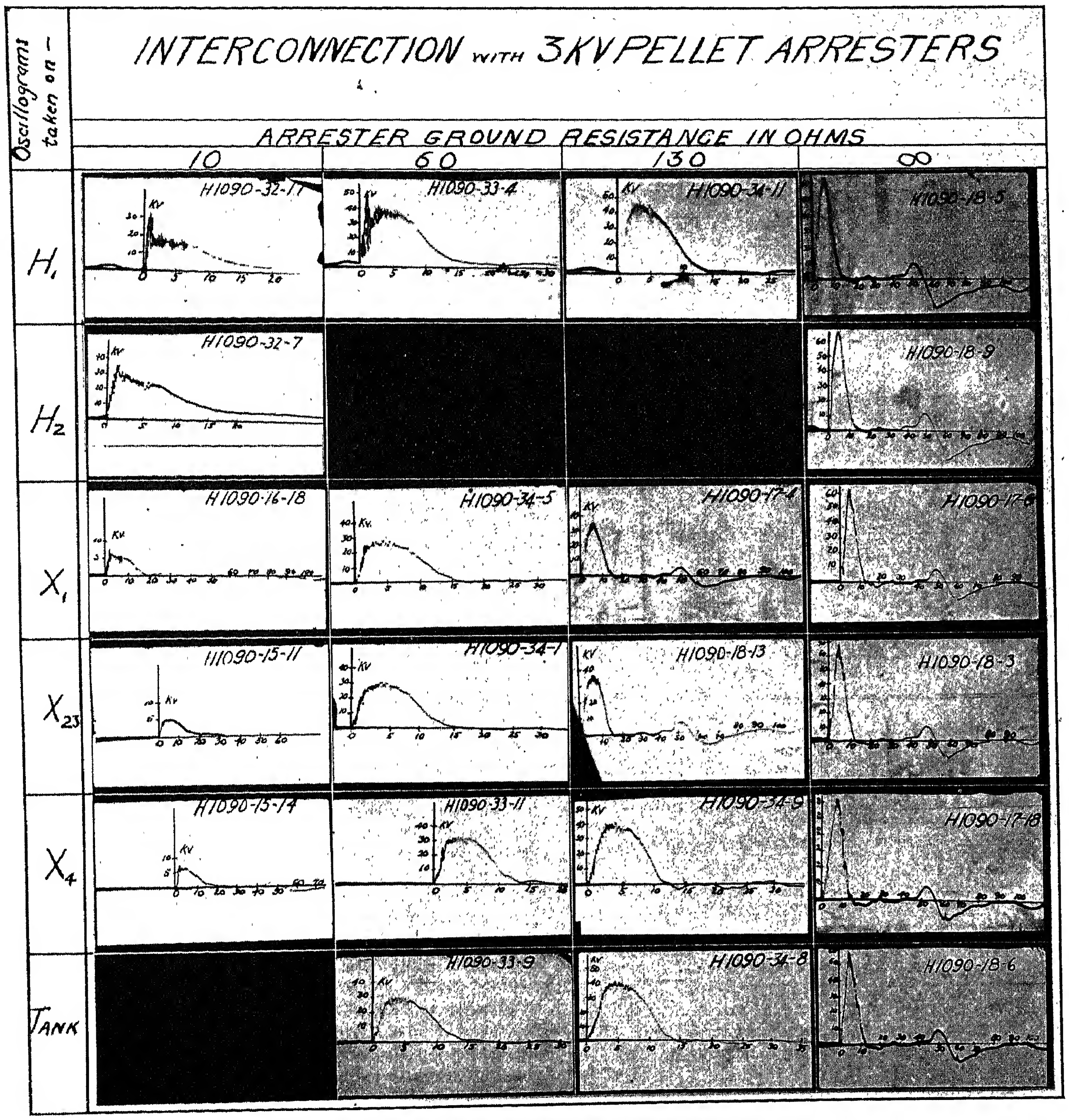

Fig. 3

all cases the interconnection prevented the flashover of the bushing.

It is regretted that insufficient time prevented the presentation, in the oral discussion, of these more recent and important tests.

K. B. McEachron: Mr. Dean's discussion giving results from three operating companies with different grounding practises is interesting and ties in very well with the results which were obtransformer failures were reduced to a very low value. If the tank is connected to the secondary neutral there will be substantially no stress between the secondary winding and the tank and there will be no tendency to flashover secondary bushings. The situation of the primary with interconnection is not materially different whether the tank is grounded to the secondary neutral or not.

From a protection point of view, connecting the primary neutral, if available, to the tank and secondary neutral with interconnected arresters, should give a very high degree of protection.

Mr. Schirmer's comments are particularly helpful from the point of view of the telephone company, especially with regard to the comparative hazard of power and lightning currents reaching the secondary. It is believed that the number of lightning discharges reaching the secondary will be somewhat increased by interconnection, however if conventional arresters are used having suitable valve elements the power current reaching the secondary will be negligible. Apparently Mr. Schirmer feels that even in cases where there are no water pipe grounds the hazard which now exists will be reduced by the use of the interconnection using proper lightning arresters.

Mr. Putman makes a statement that when the tank is grounded interconnection benefit depends on the resistance and length of customers' ground leads. This would be true only in the case where the tank was grounded to a ground independent of the secondary neutral. It is much better practise to connect the tank to the secondary neutral for which condition interconnection gives satisfactory protection.

The scheme proposed by Mr. Putman of a grounded tank with arresters connected between primary and tank with a coordinating gap to protect the low-voltage windings does not prevent lightning surges from reaching the secondary. In fact with the same ground resistance and the same arresters impulse voltages will reach the secondary circuits less frequently with the usual primary-arrester-ground connection than with the scheme proposed by Mr. Putman.

This is true because a smaller discharge is required to elevate the tank sufficiently to arc over the secondary bushings, with tank connected to separate ground, than to raise the primary conductors to high enough potential to arc over the primary bushings which are relatively much stronger than the secondary bushings. However, connection of the arrester between the primary and tank will protect the primary windings and will prevent power current from reaching the secondary. If this connection is used the secondary must withstand the discharge unless the tank is either connected to the grounded secondary neutral or to a separate ground of low enough resistance to prevent the secondary from flashing over. In general, connection of a proper arrester between primary and tank will prevent power current from reaching the secondary but will not prevent lightning from getting through unless the ground resistance is very low.

As Mr. Opsahl suspected, our tests did not show any case where power follow took place across the gaps in the "hall" fixtures, although many oscillograms were taken in which both power and impulse were applied.

The trouble experienced by Mr. Jones would be largely eliminated if the arresters were connected inside of the fuses so that arrester failure would blow the fuses.

Mr. Gay suggests the use of cable to protect the transformer. Calculation and test both show that considerable capacity is required to be of much benefit. A study of the effect of short lengths of cable on incoming waves may be found in a paper* describing an investigation made in Michigan in 1929, which shows that lengths as long as 500 ft. will have a comparatively small effect in reducing crest potentials.

Dr. Lloyd points out apparent contradictions between the results presented by Harding and Sprague and those given in the other two papers dealing with field investigations. The differences can be explained largely by differences in the magnitude of the currents flowing through ground connections. Characteristics of arresters under various conditions of wave front and crest current are well known. When such a device is connected between primary and secondary the only variation in potential which can take place is that resulting from change in wave shape or maximum current. The voltage, with interconnection, between the primary and secondary winding will not be affected to any significant degree by the presence of grounds either primary or secondary. The arrester determines the protection of the transformer while the grounds determine the potentials which are allowed to reach the consumer.

Fig. 3 shows all of the winding voltages with ground resistances of 10 ohms, 60 ohms, 130 ohms and infinite ground resistances. All other conditions were kept constant. Lack of space prevented showing these data in the paper. It should be noted that with the 10-ohm ground the secondary potential to ground was about 6 kv. crest, while it increased to 30 kv., 35 kv., and 60 kv., as the arrester ground resistance was increased from 60 ohms to 130 ohms to infinity. This increase is logical and to be expected. In studying these results one should not forget that the combined secondary neutral resistance was 35 ohms. With water pipe grounds close to the transformer it would not have been possible to elevate the secondary above ground after the negative reflections returned from the water pipe grounds.

D. W. Roper: It is impossible to find any reasonable objection to Mr. Dean's premise that a known hazard is to be preferred to an unknown hazard, but our experience leads us to a contrary conclusion. The Commonwealth Edison Company has had no accidents in connection with ungrounded transformer cases for over ten years, and, on a system with over 30,000 transformers in service, we found only one transformer with a "hot" transformer case in 1931. The Chicago experience, therefore, appears to warrant continuing the present practise of leaving the cases ungrounded.

It is interesting to note that Mr. Peek approves my suggestion that the A.I.E.E. rules for testing transformers should include suitable clauses regarding surge tests on distribution transformers. Considerable weight is added to this suggestion by the announcement of two of the larger manufacturers of distribution transformers during the discussion that they have placed lightning-proof transformers on the market.

In Chicago, the grounds to water pipes on customers' premises have a d-c. resistance of about one-half ohm. Other investigators have shown that for such low values the d-c. resistance is about the same as the surge impedance of the ground, and so we appear to be well within Mr. Fortescue's limit of two ohms.

Mr. Putman states that there is usually no ground on the secondary service of three-phase power transformers connected star delta. In Chicago, the midpoint of the secondary winding of one transformer in the bank is always grounded and hence, his objections to the use of the interconnection for such transformers do not apply here. This ground connection is made to the neutral of the lighting secondary, if available; otherwise a driven ground is used.

Answering Mr. McEachron's question, our data show that the secondary windings on banks of power transformers are about as susceptible to damage by lightning as the secondary windings on lighting transformers and that, in general the apparent entrance of lightning is twice as often on the primary windings as on secondary windings.

The recommendation for a second ground wire down the pole, which Mr. McEachron criticizes, was based on the results of tests made by Professor Harding at Purdue University and by the Westinghouse Company at its own laboratories, the records of which were not published, but are used with its permission. These tests agree in indicating a reduction of about 40 per cent in the impedance of the connection from the arrester to earth. This makes a considerable reduction in the maximum transient voltage imposed on the transformer windings when no interconnection is used. Answering Mr. Opsahl's query, we have had no practical experience with this connection, as we have very few high-resistance grounds.

Suggestion 10 of my paper, which Mr. McEachron criticizes, is based on the theory that when the density of arresters is rather

*_Study of the Effect of Short Lengths of Cable on Traveling Waves_, K. B. McEachron and H. P. Seelye, A.I.E.E. Trans., Vol. 49, 1930, p. 1432.

low, traveling waves on distribution systems become an important factor. The records of a few cases of very high transient voltages noted under the heading of "Traveling Waves" in my paper indicate that the maximum diameter of the area in which these very high-voltage transients appear is limited to something less than 1,500 ft. In Chicago, there are but few locations where the transformers are so far apart. When the transformers are located at intervals greater than 1,500 ft., the protection should partake of the class recommended for transmission lines; and for the terminals of such lines the manufacturers have hitherto recommended the installation of arresters several hundred feet distant from the terminal, in addition to those at the terminal, for the purpose of discharging a portion of the traveling wave before it reached the terminal.

Further discussion on the points Mr. Opsahl raised regarding my paper is as follows:

a. The tabulation showing the factors affecting transformer burnouts due to lightning is given in Table I of this discussion. The importance of the major factors has been shown in my papers except for previous fuse blowings; it was found that transformers which had experienced previous fuse blowings were twice as apt to fail due to lightning, as others.

TABLE I—FACTORS AFFECTING TRANSFORMER BURNOUTS

	Factor	Importance: Major	Minor
	A. DATA REGARDING THIS TRANSFORMER		
1	Size	X	
2	Make and type	X	
3	Age	X	
4	Loading record		X
5	Previous burnouts		X
6	Previous fuse blowings	X	
7	Power or lighting installation		X
8	Secondary grounded or ungrounded		X
	B. CONDITIONS AT THIS LOCATION		
9	Type of arrester	X	
10	Arrester ground resistance		X
11	Height of primary mains		X
12	Length of primary mains		X
13	Number of primary mains		X
14	Number of arresters	X	
15	Length of secondary mains		X
16	Length of phase service wires		X
17	Arrangement of primary and secondary mains		X
18	Grounded telephone cable		X
19	Shielding structures		X
20	Proximity to open ends of primaries		X
	C. CONDITIONS REGARDING NEIGHBORHOOD		
21	Burnouts, this storm		X
22	Burnouts, 5-year period		X
23	Fuse blowings, this storm		X
24	Fuse blowings, 5-year period		X
25	Density of arresters	X	
		7	18

b. Careful attempts on coordination between failures of watthour meters due to lightning, and transformer or fuse blowings due to lightning, resulted in our being able to find that such troubles occurred at the same time in only a small percentage of the cases.

c. Our data on the effect of arrester ground resistance on transformer burnouts due to lightning have shown that the resistance is not a predominating variable in our system, where over 90 per cent of the resistances in recent years have been less than 50 ohms. In trying to correlate burnouts with magnitude of resistance, it has been noted that the ground resistance of the arrester on the transformer that burned out might be considerably lower or higher than the arrester ground resistances for adjacent transformers.

The high resistance areas are fairly well defined in Chicago, and they are practically all in regions where the density of arresters is high. A large fraction of the burnouts, however, occur in outlying districts where the density is low and the ground resistance is also low. This situation means that whether or not a transformer is to burn out is not primarily determined in Chicago by the magnitude of the resistance, but by the location of the lightning discharge and by the density of arresters. The existence of the arrester ground does not determine the location or intensity of a lightning discharge, but the resistance may affect the amount of damage to the transformer if it is very high.

d. Our experience and statistics indicate that the use of the interconnection should have little, if any, effect on the hazards to the customer and these hazards at the present time are negligible. A careful study of our records over the past few years show that troubles on customers' premises occur in a few localities each year and the cost of repairing the damaged customers' equipment has been about $200 per year.

Mr. Ekvall thinks that the Philadelphia system of installing arresters on only a part of the transformers in order to get the amount of improvement resulting from the installation of arresters is superior to the system used in Chicago in recent years. The plan favored by Mr. Ekvall was used in earlier years in Chicago, and the results were reported by the writer in a paper before the N.E.L.A. which appears in the Report of the Technical and Hydroelectric Session for 1916, page 86. In those early days we had the same idea as that expressed by Mr. Ekvall, namely, that by some system of records, it would be possible to eliminate the lightning as a variable; but, as expressed in my paper under the heading, "Accuracy of Results," "In spite of all attempts to eliminate the lightning as a variable . . . lightning still remains the dominant variable." If Mr. Ekvall and his associates have been able by their system of records and their analysis to eliminate the lightning as a variable, they are to be congratulated. Perhaps, however, they will change their opinion on this and several other points, as we did in Chicago, with a few more years' experience. It is, of course, very much easier to draw conclusions when only a few facts are available.

Mr. Ekvall criticizes the methods used in Chicago for determining the relative amount of trouble with various sizes of transformers, but his criticism appears to have been answered by Mr. Putman.

T. H. Haines and C. A. Corney: In Mr. K. B. McEachron's discussion he mentions a protective device which was used in Boston for some years previous to the general use of arresters. Mr. McEachron refers to the primary-secondary contact resulting from each operation of the device as being likely to increase the hazard on customers' premises where all grounds in a building are not tied together. It will be of interest to note that although in use for many years and in various locations no serious trouble has ever developed from this cause.

Mr. McEachron calls attention to the result of certain of his calculations which tend to show that complete protection of a distribution transformer connected to an average distribution line cannot be expected with lightning arrester ground resistances in excess of 80 ohms. This need not be interpreted to mean, however, that quite adequate protection cannot be obtained with a ground resistance of 200 ohms or higher, as many induced potentials are less than the maximum which the line can stand and many transformers can and do stand greater potentials than may be assumed as an average value. Experience in Boston where ground resistances are high by comparison with many other districts clearly indicates a marked improvement in the trouble rate due to lightning as a result of the application of lightning arresters. Undoubtedly troubles might be still further reduced with lower ground resistance value, but such protection as is obtained under existing conditions is considered adequate to warrant the application of arresters.

In Mr. A. M. Opsahl's discussion he asks what ground resistances can be attained at the customers' premises under conditions in the Boston territory. In general the customers'

grounds are of lower resistance than lightning arrester grounds principally because they are connected to water pipes. This does not apply to outlying territory where water pipes are not available and as a result both types of grounds should be much alike. Secondary network grounds should, of course, be better than lightning arrester grounds due to there usually being more than one ground connection on each secondary network.

In answer to his further questions, we find that our transformer flashovers usually take place over the bushings and at the terminal boards, and that no serious trouble is encountered on the secondary circuits or on customers' premises.

Mr. Herman Halperin requests information on the trouble in the unprotected area where no lightning arresters are installed.

The following table will answer his question.

LIGHTNING TROUBLES IN UNPROTECTED AREA

		Troubles per 100 transformers			
Year	Total transformers	Fuses	Miscellaneous defects	Windings defective	Total troubles
1927	3,070	8.5	4.0	0.2	12.7
1928	3,337	3.3	1.5	0.2	5.0
1929	3,353	4.7	3.5	0.3	8.5
1930	3,450	1.9	2.4	0.3	4.6
1931	3,511	1.6	1.7	0.2	3.5

H. A. Dambly, H. N. Ekvall, and H. S. Phelps: In reply to the questions raised by Mr. A. H. Schirmer and Dr. M. G. Lloyd regarding grounding requirements where the neutral tie is used, we wish to offer the following comments.

As stated in the paper, the neutral tie connection was used in Philadelphia for the first time in 1931. For this trial application, consisting of 151 transformer locations, it was decided to limit the installations to locations where the secondary neutral ground grid consisted of 10 or more water pipe grounds, the ground network to measure not more than 15 ohms resistance. It is realized that these limitations may be unnecessarily conservative.

Mr. Roper expressed preference for the kva-hr. basis over the customer-hr. basis for analyzing customer interruptions. We believe that the kva-hr. basis emphasizes the inconvenience to the large customers, whereas our experience seems to indicate that the customer-hr. basis gives a more complete picture of the inconvenience to customers as a whole. Constant effort to maintain good public relations makes it essential to consider trouble from the standpoint of the largest number of customers.

Messrs. Andrews and Hendrickson believe that high ground resistance in the Philadelphia territory has been partly responsible for arresters being of little or no value on transformers smaller than 15 kva. In their territory, in the section of Joliet, Illinois, where grounds are of lower resistance than in Philadelphia, they found arresters to give considerable protection to the small transformers. Their data show approximately one-half the rate of trouble on protected as on unprotected transformers, 95 per cent of which was below 15 kva. However, if their data were analyzed with respect to transformer size, it would probably be found that the majority of protected transformers are of a larger size than the unprotected. If this is the case then their apparently good arrester performance is most likely due to the fact that transformers of the larger sizes are much less susceptible to lightning trouble than the smaller sizes.

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